Optical Pumping

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Measurement of the Zeeman splittings of the ground state of the natural rubidium isotopes; measurement of the relaxation time of the magnetization of rubidium vapor; and measurement of the local geomagnetic field by the rubidium magnetometer. Rubidium vapor in a weak (∼.01-10 gauss) magnetic field controlled with Helmholtz coils is pumped with circularly polarized D1 light from a rubidium rf discharge lamp. The degree of magnetization of the vapor is inferred from a differential measurement of its opacity to the pumping radiation. In the first part of the experiment the energy separation between the magnetic substates of the ground-state hyperfine levels is determined as a function of the magnetic field from measurements of the frequencies of rf photons that cause depolarization and consequent greater opacity of the vapor. The magnetic moments of the ground states of the ^{85}Rb and ^{87}Rb isotopes are derived from the data and compared with the vector model for addition of electronic and nuclear angular momenta. In the second part of the experiment the direction of magnetization is alternated between nearly parallel and nearly antiparallel to the optic axis, and the effects of the speed of reversal on the amplitude of the opacity signal are observed and compared with a computer model. The time constant of the pumping action is measured as a function of the intensity of the pumping light, and the results are compared with a theory of competing rate processes - pumping versus collisional depolarization.

PREPARATORY PROBLEMS

1. With reference to Figure 1 of this guide, estimate the energy differences (order of magnitude) in eV between each of the following pairs of states of Rb:

   (a) $5^2S_{1/2} - 5^2P_{3/2}$

   (b) $5^2P_{1/2} - 5^2P_{3/2}$

   (c) $5^2S_{1/2}(f = 2) - 5^2S_{1/2}(f = 3)$

   (d) $5^2S_{1/2}(f = 2, m_f = -1) - 5^2S_{1/2}(f = 2, m_f = 0)$ in a magnetic field of 1 gauss.

2. Derive the Landè g-factors for the ground state of the two rubidium isotopes using either the vector model or matrix mechanics for the addition of angular and magnetic moments.

3. In thermal equilibrium at 320K how many atoms in a mole of rubidium would one expect to find in the $5^2P_{1/2}$ state? What is the difference in the population of the lowest and highest magnetic substate of the ground state in a field of 1 gauss at that temperature?

4. Given two plane polarizing filters and a quarter wave plate, how do you make a beam of circularly polarized light?

5. What fractional contributions does the nucleus of a rubidium atom make to its (a) angular momentum (b) magnetic moment?

6. If the earth's field were that of a magnetic dipole at the center and parallel to the rotation axis, then what would be the direction of the field at the latitude of Boston?

Some useful constants are Bohr Magneton: $\mu_B \equiv \frac{eh}{4\pi m_e c} = 9.1\times10^{-21}$ ergs/gauss Nuclear Magneton: $\mu_N \equiv \frac{eh}{4\pi m_p c} = 5.0 \times 10^{-24}$ ergs/gauss

The magnitude of the magnetic moment of a nucleus is $g_n\mu_n\sqrt{I(I+1)}$, where I is the angular momentum quantum number of the nucleus, μ_n is the nuclear magneton, and g_n is a gyromagnetic ratio arising from the configuration of the nucleons themselves. Empirically determined values for g_n are:

$g_n = 1.3527$ for ^{85}Rb with I = 5/2 $g_n = 2.7505$ for ^{87}Rb with I = 3/2

INTRODUCTION

A. Kastler discovered optical pumping in the 1950's and received the Nobel Prize for his work in 1966. In this experiment you will explore the phenomenon of optical pumping and its application to fundamental measurements in atomic and nuclear physics with equipment originally built for the Junior Lab shortly after the publication of Kastler's work. Various improvements have been made since then. Though its components are simple, the apparatus is capable of yielding accurate results that illustrate several of the fundamental principles of quantum theory and atomic structure. Among other possibilities it can be used to measure collisional relaxation phenomena, and the magnitude and direction of the local geomagnetic field.

ANGULAR MOMENTUM AND ATOMIC STRUCTURE

We will be concerned with the angular momentum and energy of neutral atoms of rubidium in a vapor under

conditions in which each atom can be treated as a nearly isolated system. Such a system in field free space has eigenstates with definite values of the square of the total angular momentum, $\vec{F} \cdot \vec{F}$, and of the component of angular momentum with respect to some given direction, F_z . According to the laws of quantum mechanics the eigenvalues of $\vec{F} \cdot \vec{F}$, and F_z are given by the expressions

$$\vec{F} \cdot \vec{F} = f(f+1)\hbar^2 \tag{1}$$

and

$$F_z = m_f \hbar \tag{2}$$

where f is an integer or half-integer, and m_f has one of the $2f+1$ values $-f, -f+1, ..., f-1, f$. In the absence of any magnetic field, the eigenstates with the same f but different m_f are degenerate, i.e. they have the same energy. However, an atom with angular momentum F generally has a magnetic moment

$$\vec{\mu} = g_f \frac{e}{2m} \vec{F} \tag{3}$$

where m is the electron mass, e is the magnitude of the electron charge, and g is a proportionality constant called the Lande g factor. If an external magnetic field is present, then the degeneracy will be lifted by virtue of the interaction between the external magnetic field and the magnetic moment of the atom. If the external field is sufficiently weak so that it does not significantly alter the internal structure of the atom, then the energy of a particular magnetic substate will depend linearly on the field strength, B, and the value of m_f according to the equation

$$E = E_0 + g_f m_f \mu_B B \tag{4}$$

where E_0 is the energy of the eigenstate in zero field and $\mu_B = \frac{eh}{4\pi mc}$ is the Bohr magneton. The g factor depends on the quantum numbers of the particular state and is of order unity. The difference in energy between magnetic substates in a magnetic field is called the magnetic, or Zeeman, splitting. By measuring this splitting in a known field one can determine the value of $g_f \mu_B$. Alternatively, given the value of $g_f \mu_B$ one can use a measurement of the splitting to determine the magnitude of an unknown magnetic field.

A rubidium atom contains nearly 300 quarks and leptons, each with an intrinsic angular momentum of $\frac{\hbar}{2}$. Triplets of quarks are bound by the "color" force to form nucleons (protons and neutrons) with dimensions of the order of 10^{-13}cm. The nucleons are bound in nuclei with dimensions of the order of 10^{-12}cm by the remnants of the color force which "leak" out of the nucleons. Charged leptons (electrons) and nuclei are bound by electromagnetic force in atomic structures with dimensions of the order of 10^{-8}cm. Atoms are bound in molecules by electromagnetic force. Each of these structures - nucleons, nuclei, atoms and molecules - can exist in a variety of states. However, the lowest excited states of nucleons and nuclei have energies so far above the ground states that they are never excited in atomic physics experiments. Moreover, the size of the nucleus is tiny compared to the size of the electronic structure of the atom. Thus, for the purposes of understanding all but the most refined measurements of atomic structure, the nucleus and all it contains can be considered as a point particle characterized by its net charge, angular momentum, magnetic dipole moment, and in some circumstances, weak higher electric and magnetic moments. The problems of atomic physics are thereby reduced to that of understanding how the electrons and nucleus of an atom interact with one another and with external fields.

According to the shell model, the electronic configuration of rubidium is

$1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 5s = 5^2S_{1/2}$

which specifies 36 electrons in closed (i.e. subtotal angular momentum=0) shells with principal quantum number n from 1 to 4 plus a single "optical" electron in a 5s orbital. The letters s, p, and d denote the electron "orbitals" with orbital angular momentum quantum numbers l=0, 1, and 2, respectively. (Note the 5s shell begins to fill before the 4d). The overall designation of the electronic ground state is $5^2S_{1/2}$, which is called "five doublet S one-half." "Five" specifies the principal quantum number of the outer electron. "S" specifies that the total orbital angular momentum quantum number of the electrons is zero. The term "one-half" refers to the subscript 1/2 which specifies the total angular momentum quantum number of the electrons. With only one electron outside the closed shells the total angular momentum of the ground state is due to just the spin of the outer electron. "Doublet" refers to the superscript 2=$2s$ +1 where s=1/2 is the total spin angular momentum quantum number; the word characterizes the total spin by specifying the number of substates that arise from the combinations of $\vec{L}$ and $\vec{S}$. In the alkali metals this amounts to a two-fold "fine structure" splitting of the energy levels of excited electronic states with $l \geq 1$ due to the interaction of the magnetic moments associated with the spin and orbital angular momenta of the outer electron. In such states the orbital and spin angular momenta can combine in just two ways to give $j = l \pm 1/2$. Just as in the case of two bar magnets pivoted close to one another, the state of lower energy is the one in which the spin and orbital magnetic moments are anti-parallel and the total (electronic) angular momentum quantum number is $j = l - 1/2$. The word "doublet" is retained for S states even though there is no spin-orbit interaction because $l = 0$, and consequently the ground state has no

fine structure substates [5].

With the shell model as a framework one can explain quantitatively many of the low-energy atomic phenomena, like those involved in the present experiment, in terms of the following hierarchy of interactions, arranged in order of decreasing energy:

1. Interaction between the outer electron(s) and the combined coulomb field of the nucleus and inner closed-shell electrons, giving rise to states specified by the principal quantum numbers and the orbital angular momentum quantum numbers of the outer electrons and differing in energy by $\Delta E \approx 1eV$

2. Interaction between the magnetic moments associated with the spin and orbital angular momenta of the outer electron(s), giving rise to "fine structure" substates differing in energy by $\Delta E \approx 10^{-3}eV$

3. Interaction between the total electronic magnetic moment and the magnetic moment of the nucleus, giving rise to "hyperfine structure" substates with $\Delta E \approx 10^{-6}eV$

4. Interaction between the total magnetic moment of the atom and the external magnetic field.

The torque resulting from the interaction between the magnetic moments associated with the spin and orbital angular momenta of the electrons causes $\vec{L}$ and $\vec{S}$ to precess rapidly about their sum $\vec{J} = \vec{L} + \vec{S}$. The much weaker interaction between the magnetic moments associated with $\vec{J}$ and the nuclear angular momentum $\vec{I}$ causes $\vec{J}$ and $\vec{I}$ to precess much more slowly about their sum $\vec{F} = \vec{J} + \vec{I}$. And finally a weak external magnetic field $\vec{B}$ exerts a torque on the magnetic moment associated with $\vec{F}$ that causes it to precess about $\vec{B}$ even more slowly. However, if the external field is sufficiently strong that the precession frequency of $\vec{F}$ about $\vec{B}$ approaches that of $\vec{J}$ and $\vec{I}$ about $\vec{F}$, then the dependencies of the separations between the substates on the external field become nonlinear, and the separations become unequal.

The angular momentum quantum numbers of the rubidium nuclei are i=5/2 for ^{85}Rb and i=3/2 for ^{87}Rb. According to the rules for adding angular momenta, the total angular momentum quantum number of the atom must be one of the values $j+i, j+i-1, j+i-2, ...|j-i+1|, |j-i|$. Thus each electronic state with a certain value of j is split into a number of hyperfine substates equal to $2j$+1 or $2i$+1, whichever is the smaller, with a separation in energy between substates that depends on the strength of the magnetic interaction between the total magnetic moment of the electrons and the magnetic moment of the nucleus. Since j =1/2 in the ground state, the number of hyperfine substates is just 2, and the values of f are 5/2+1/2=3 and 5/2-1/2=2 for ^{85}Rb and 3/2+1/2=2 and 3/2-1/2=1 for ^{87}Rb.

The magnetic moments of nuclei are of the order of the nuclear magneton which is smaller than the Bohr magneton by a factor equal to the ratio of the proton mass to the electron mass, i.e about 2000 times smaller. Thus, regardless of how the electronic and nuclear angular momenta are combined, the nuclear magnetic moment makes a small contribution to the total magnetic moment of the atom. However, the nuclear angular momentum, quantized in units of $\hbar$ like the electronic angular momentum, makes a major contribution to the total angular momentum of the atom and, therefore, to any properties that depend on how the angular momenta are combined such as the Landè g factor and the multiplicities of magnetic substates.

Figure 1a-d and 2a-d are schematic energy level diagrams for the ground and lowest excited states of ^{85}Rb and ^{87}Rb in a weak magnetic field, showing how the ground and first excited electronic states can be imagined to split into successive sublevels as the various interactions mentioned above are "turned on". The energy scale is grossly distorted in order to display the hierarchy of structure in one figure. In fact, the separations between the Zeeman levels in a weak external field of $\approx$ 1 gauss are $\approx 10^8$ times smaller than the separation between the unperturbed 5S and 5P levels. Figures 1d and 2d represent the specific level structures with which we will be dealing in this experiment.

In the two lowest excited electronic states, designated $5^2P_{1/2}$ and $5^2P_{3/2}$, the valence electron has orbital angular momentum quantum number l =1. This combines with the electron spin to give a total electronic angular momentum quantum number j of 1/2 or 3/2. The energies of these two states differ by virtue of the "fine structure" interaction between the spin and orbital magnetic moments of the outer electron. Transitions from the hyperfine and magnetic substates of $5^2P_{3/2}$ and $5^2P_{1/2}$ to the hyperfine and magnetic substates of 5S produce photons in two narrow optical spectral regions called the rubidium D-lines at 7800Åand 7948Å. Transitions between the various energy levels can occur under a variety of circumstances, which include the following of particular interest in this experiment:

1. Electric dipole transitions between the 5S and 5P states; a) either absorption or stimulated emission induced by interactions with optical frequency photons having energies close to the energy difference between two atomic states. b) spontaneous emission Electric dipole transitions are restricted by the selection rules $\Delta l = \pm 1$, $\Delta f = 0$ or ± 1 except not $f = 0$ to f=0, $\Delta m_f = 0$ or ± 1

2. Magnetic dipole transitions between magnetic substates induced by radio frequency photons with energies close to the energy differences of two Zeeman levels The selection rule is $\Delta m_f = \pm 1$.

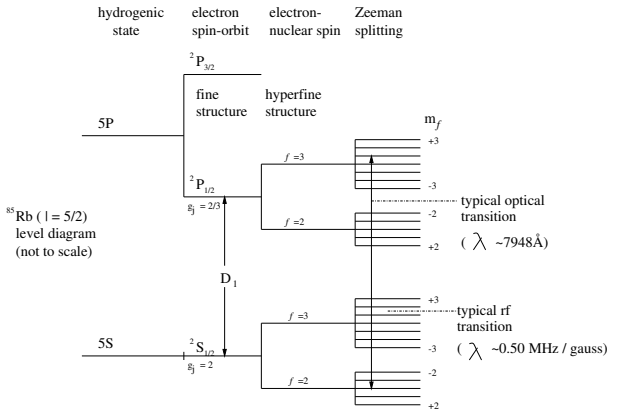

FIG. 1: Energy levels (not to scale) of ^{85}Rb as successively weaker interactions are turned on.

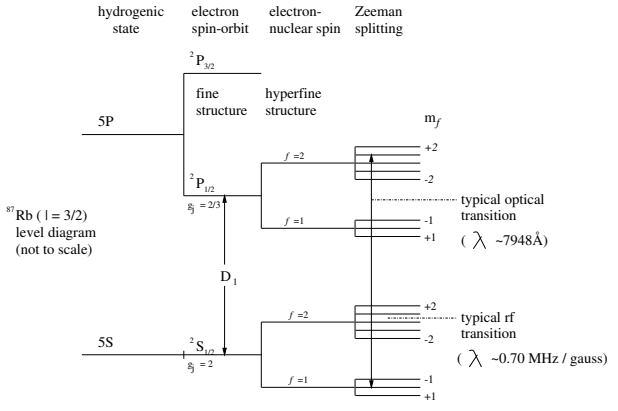

FIG. 2: Energy levels (not to scale) of ^{87}Rb as successively weaker interactions are turned on.

3. Collision-induced transitions between the magnetic substates.

OPTICAL PUMPING

Under conditions of thermal equilibrium at temperature T the distribution of atoms among states of various energies obeys the Boltzmann distribution law according to which the ratio $\frac{n_1}{n_2}$ of the numbers of atoms in two states of energy E_1 and E_2 is

$$\frac{n_1}{n_2} = exp\left(\frac{E_2 - E_1}{kT}\right) \tag{5}$$

where $k = 8.62 \times 10^{-5}$ eV K^{-1} is the Boltzmann constant. With this formula we can calculate the fraction of rubidium atoms in the first excited electronic state in a vapor at room temperature for which $kT \approx 0.03eV$. The first excited state lies about 2 eV above the ground state. The Boltzmann factor is therefore $\approx exp^{-67} \approx 10^{-29}$, which implies that only about one atom in 10 kilograms

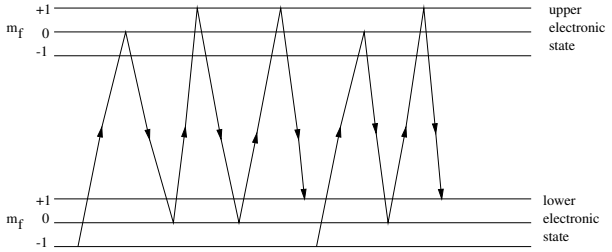

FIG. 3: Schematic histories of several atoms with magnetic substates undergoing optical pumping by circularly polarized light in a magnetic field.

is in an excited state at any given moment. On the other hand, the differences between the energies of magnetic substates in the weak fields used in this experiment are very small compared to kT at the temperature of the rubidium vapor. Thus, under equilibrium conditions, there is only a slight difference in the populations of the magnetic substates.

Optical pumping is a process in which absorption of light produces a population of the energy levels different from the Boltzmann distribution. In this experiment you will irradiate rubidium atoms in a magnetic field with circularly polarized photons in a narrow range of energies such that they can induce $5^2S_{1/2} \rightarrow 5^2P_{1/2}$ dipole transitions. However, absorption can occur only if the total angular momentum of the incident photon and atom is conserved in the process. If the incident photons have angular momentum $+\hbar$, the only allowed transitions are those in which $\Delta m_f = 1$. Thus every absorption produces an excited atom with one unit more of projected angular momentum than it had before the transition. On the other hand, the spontaneous and rapid ($\approx 10^{-8}s$) $5^2P_{1/2} \rightarrow 5^2S_{1/2}$ decay transitions occur with only the restriction $\Delta m_f = 0$ or ± 1. The net result is a "pumping" of the atoms in the 5S magnetic substates toward positive values of m.

The process is illustrated schematically in Figure which depicts the histories of several atoms which are initially in various magnetic substates of a lower electronic state. Under irradiation by circularly polarized light they make upward transitions to magnetic substates of an upper electronic state subject to the restriction $\Delta m_f = +1$. Spontaneous downward transitions occur with $\Delta m_f = \pm 1, 0$. When an atom finally lands in the $m_f = +1$ substate of the lower electronic state it is stuck because it cannot absorb another circularly polarized photon.

The rate of spontaneous transitions among the magnetic substates is small. To reduce the rate of depolarizing collisions, the rubidium vapor is mixed with a "buffer" gas (neon) which has no magnetic substates in its ground electronic state and is therefore unable to absorb or donate the small quanta of energy required for magnetic substate transitions. The buffer atoms shield

the rubidium atoms from colliding with one another and slow their diffusion to the walls. With the field in the direction of the beam, the most positive substate may be the one of highest energy. Alternatively, with the field in the opposite direction, that same substate would be the one of lowest energy. In either case the population of the extreme substate, whichever it may be, will increase at the expense of the other substates until, as in the actual experiment, there are few atoms left which can absorb the incident circularly polarized photons. Thus the intensity of the transmitted beam increases as the absorbing ability of the vapor diminishes, and it approaches an asymptotic value determined by the rate at which depolarizing collisions restore the atoms to substates which can absorb the polarized photons. In effect, the vapor is magnetically polarized and optically "bleached" by the process of optical pumping, and the resulting distribution of the atoms among their possible quantum states is grossly different from the Boltzmann distribution. (The absorption of the photons also gives rise to a non-Boltzmann population of the $5^2P_{1/2}$ states, but the decay by electric dipole transitions is so rapid that the fraction of atoms in those states at any given time remains extremely small).

In principle, the population of the magnetic substates could be changed by simply turning the beam on and off with a mechanical chopper. Immediately after each turn-off depolarizing collisions would restore thermal equilibrium. When the beam is turned on again one would observe an opacity pulse, i.e. a transmission through the vapor which starts low and increases toward an asymptotic value as the pumping action proceeds and the balance between pumping and collisional depolarization is approached. However, this method has problems caused by the large changes in the signal levels when the pumping beam is turned on and off.

In the present experiment the intensity of the circularly polarized beam is kept steady and changes in the polarization of the vapor are produced by either 1) flooding the vapor with radio photons of the requisite resonant frequency and polarization to induce transitions between the magnetic substates by absorption and/or stimulated emission, or 2) suddenly changing the magnetic field.

With radio photons of the resonance frequency, rapid transitions are induced between the magnetic substates so their populations are kept nearly equal in spite of the pumping action and the vapor can absorb the circularly polarized optical photons. The resonant frequency, indicated by an increase in opacity, is a direct measure of the energy difference between the magnetic substates. Knowing the magnetic field and the resonant frequency, one can derive the value of the magnetic moment of the rubidium atom.

To see how the transitions are induced by a resonance rf field we represent the weak ($\ll 0.2$ gauss) linearly polarized rf magnetic field vector as a sum of two circularly polarized component vectors according to the identity

$$\vec{B}_{rf} = B_{rf}[\cos\omega t, 0, 0] = \frac{B_{rf}}{2}[\cos\omega t, \sin\omega t, 0] + \frac{B_{rf}}{2}[\cos\omega t, -\sin\omega t, 0] \quad (6)$$

where $\omega = \gamma B_0$ is the the Larmor precession frequency of the dipoles in the strong ($B_0 \approx 0.2 gauss$) DC field, $\gamma = \frac{g_F e}{2mc}$ is the gyromagnetic ratio of the atoms, and g_F is the Lande g factor. If we confine our attention to the circular component of the rf field rotating in the same sense as the Larmor precession of the moments, then we have the situation discussed by Melissinos (1966, page 344) in the context of nuclear magnetic resonance.

The effects of changing the Z-component of the field on the opacity of the vapor undergoing magnetic pumping depend on the speed, sign and amplitude of the change. One can study the behavior of polarized moments in changing fields and the depolarizing interactions in the vapor by observing the size and shapes of the resulting opacity pulses. The effect on the polarization of changing the field can be described as the effect of a changing torque on a gyroscope. It turns out that the motion of the net angular momentum, $\vec{L}$, of an ensemble of atoms in a magnetic field is governed by the classical equation

$$\frac{d\vec{L}}{dt} = \gamma\vec{L} \times \vec{B} \quad (7)$$

where $\vec{B}$ is the magnetic field, and γ is the gyromagnetic ratio of the individual atoms (Abragam 1961). If $\vec{B}$ is steady, the motion is a precession about the field direction with angular velocity γB and a constant value of the angle between $\vec{L}$ and $\vec{B}$. If $\vec{B}$ changes direction at a rate that is small compared to γB, then the angle between $\vec{L}$ and $\vec{B}$ will remain nearly constant, i.e. $\vec{L}$ will, in effect, follow $\vec{B}$. If, on the other hand, $\vec{B}$ changes direction at a rate that is large compared to γB, as in the case where one of its components passes through zero, then $\vec{L}$ cannot follow $\vec{B}$, and the angle between $\vec{L}$ and $\vec{B}$ can change radically. The effect of the field change on the polarization can be deduced from an observation of its effect on the opacity of the vapor. A LabVIEW program called "Optical Pumping Simulation.vi" available on the Junior Lab server can be used on the Junior Lab PC's to explore these effects (see Appendix A).

APPARATUS

Figure 4 is a schematic diagram of the apparatus. Photons with energies in the narrow range in which they can induce $5^S_{1/2} \rightarrow 5^P_{1/2}$ transitions are obtained from a rubidium vapor lamp excited by a radio frequency generator. The latter subjects the vapor to a rapidly oscillating, high amplitude electric field. The result is an "rf

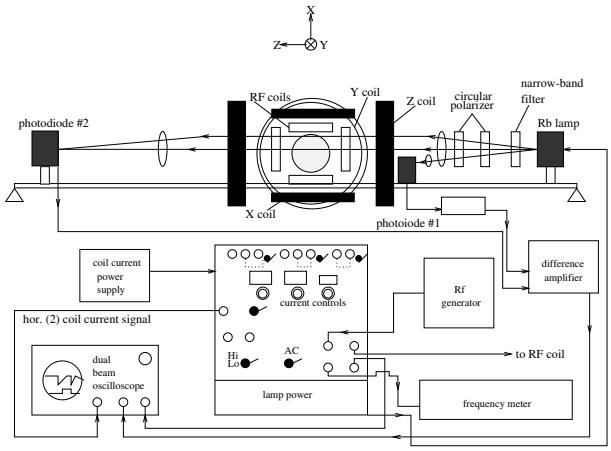

FIG. 4: Schematic diagram of the apparatus and electrical control and display equipment. The indicated connections are for the measurement of the magnetic field reversal effects. located at the center of three mutually perpendicular Helmholtz coils with which all three components of the magnetic field in the bulb can be controlled. Finally the beam is focussed onto photodiode 2 whose signal is to be compared with that from photodiode 1. When everything is properly adjusted, the measurement chain yields a signal proportional to the difference between the signals from the two photodiodes, as when the opacity of the vapor in the bulb changes by virtue of a change in the number of atoms able to absorb the circularly polarized D_1 photons. Z-coils: 180 turns of #18 magnet wire (0.040"), 21.75" ID, 22.25" OD, 12-5/16" inner separation, 15-5/16" outer separation. X-coils: 50 turns, 34.8cm ID, 37.2cm OD, 7-7/8" inner separation, 8-1/4" outer separation.

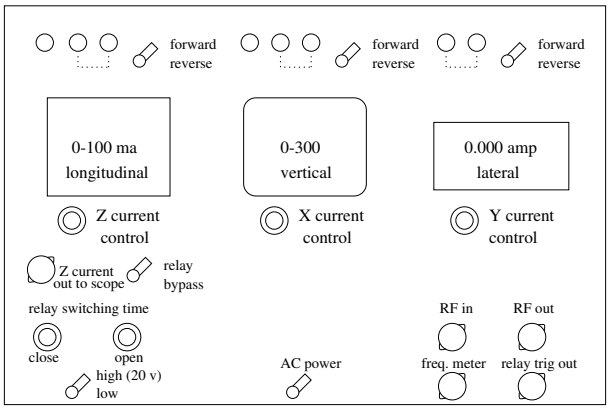

FIG. 5: Layout of the control panel. **Note that in order to access lower currents with the Z-axis current control, a 10-turn, $\sim 1000\Omega$ potentiometer must be used as the jumper.** The connections shown between the two chassis are for the measurement of the effects of field reversal.

discharge" in which free electrons are driven back and forth with sufficient energy to maintain a state of partial ionization as well as to excite valence electrons to the 5^2P and higher levels. Some of the photons emitted in the decay of excited states pass through a narrow-band interference filter that transmits only the lower energy photons of the D-line doublet, i.e. the D1 photons produced in $5^S_{1/2} \rightarrow 5^S_{1/2}$ transitions and having wavelengths close to 7948Å. The D1 photons have an energy distribution whose width, determined by pressure and Doppler broadening in the lamp, is sufficiently large to encompass the spread in energy differences between all the $5^S_{1/2}$ and $5^P_{1/2}$ magnetic substates.

Next the beam passes through a combination of linear polarizer and quarter-wave plate that transmits only photons with one sense of circular polarization, which means that every transmitted photon has a component of angular momentum in the direction of the beam equal to $\pm\hbar$, as the case may be. A portion of the beam strikes photodiode 1 which acts as a beam monitor. The rest traverses rubidium vapor and a "buffer" gas (neon) contained at low pressure in a glass bulb.

The rubidium vapor absorption cell is enclosed in a plexiglass oven which allows you to control the vapor pressure of rubidium by adjusting the temperature (melting point of rubidium = 38.5°). In addition to rubidium vapor, the cell contains neon gas at a pressure of several mm of mercury. The RF coil is used to irradiate the vapor with very low-energy RF photons to induce transitions between the magnetic substates and thereby depolarize the pumped rubidium atoms. Changes in the difference between the intensity incident on the vapor and the intensity transmitted are measured by the two solid state photodiodes connected to a difference amplifier. The amplified difference is displayed on one trace of a dual beam oscilloscope. A signal proportional to the current in the Z-axis Helmholtz coils can be displayed on the other trace.

Figure is a diagram of the control panel. Figure wiring diagram of the control circuit.

NOTE: Electronic equipment and ferromagnetic materials which might have significant effects on the magnetic field should be kept at least a meter away from the vapor cell.

Information on the operation of each component of the setup follows:

LIGHT SOURCE

The rubidium lamp is a small evacuated glass bulb containing rubidium placed between two coils energized by an RF power supply within the source box. To turn on the lamp:

1. Switch on the lamp power supply; the other switch on the power supply should be kept at standby.

2. Let the vacuum tubes warm up for about about 1 minute, and then turn the standby switch to ON. The lamp should glow violet within a few minutes. If the lamp does not ignite ask for help.

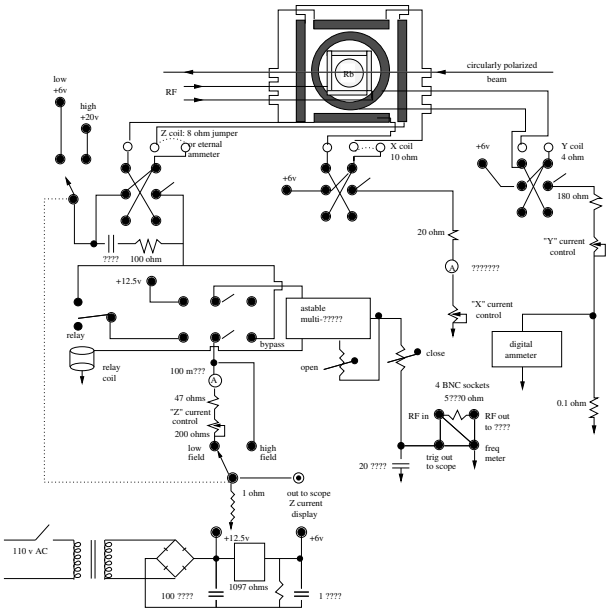

FIG. 6: Wiring diagram of the control circuit for the Helmholtz coils. High-field (> 100 mA) is obtained by means of an external 20 VDC power supply with voltage and current controls. An external ammeter is required for measuring current in the high-field range. The relay/bypass should be put in the bypass position.

3. The lamp should reach a stable operating condition (mainly a matter of establishing temperature equilibrium in the lamp) in about 30 minutes. **You should turn on the Rb lamp at the very beginning of a lab session due to this length time required for equilibration.**

OPTICS

Position the two lenses so that the beam is nearly parallel as it traverses the vapor and an image of the light source is focused on the hole that admits light to photodiode 2. The DC levels from the two photodiodes can be compared using the oscilloscope. They should be approximately equal in magnitude and not exceed 5 volts to avoid saturation and consequent loss of linearity and sensitivity. Final precise equalization is achieved with the attenuator and the difference amplifier controls.

Arrange a polarizing filter and a quarter wave plate so as to circularly polarize the beam entering the bulb containing the rubidium vapor. Near th apparatus you will find a supply of linear polarizers, quarter wave plates, and optical bench mounts with which you can construct and test a circular polarizing system. (Avoid touching the optical surfaces with your fingers.) When you are satisfied that you have a combination that works, mount it between the interference filter and lens 1. Readjust the attenuator to equalize the signals if necessary. (You may have to insert a neutral density filter to reduce the beam intensity and thereby avoid saturating the photodiodes.)

DIFFERENCE AMPLIFIER

Photodiode 2, receiving light that has been transmitted through the rubidium vapor, responds both to changes in the opacity of the vapor and changes in the lamp brightness. Photodiode 1 responds just to changes in the lamp brightness. If the two are accurately balanced, then the difference between their signals will be sensitive only to the changes in the opacity. The two signals are fed to the dual inputs of a difference amplifier whose output is displayed on one beam of a dual beam oscilloscope.

Proper operation of the system requires that both photodiodes be operating in a linear range and that the signals fed into the difference amplifier due to the DC components of their lamp illuminations be precisely equal. Otherwise, fluctuations in the lamp brightness will affect the signal from one photodiode more than the other and cause the output of the difference amplifier to wander around erratically so as to make useful measurements virtually impossible. To minimize sensitivity of the signal to mechanical vibrations it is important to focus the beam so that it enters the hole leading to photodiode 2 without hitting the sides of the hole.

RF GENERATOR

The radio frequency (RF) generator should be connected to "RF in" on the control chassis (see Figures 5 and 6) and the "RF out" to the small cotton-insulated coils within the plastic box containing the rubidium vapor cell. The coils emit RF photons linearly polarized in the Y direction that excite transitions between the magnetic substates of the $5^S_{1/2}$ electronic ground state.

SWITCHING CIRCUIT

Reversal of the longitudinal (Z) component of the magnetic field in the vapor is accomplished by setting the current in the Z-axis Helmholtz coils so as to produce a field opposite to and larger than the Z-component of the earth's field. Switching the coil current on and off then reverses the net Z-component of the field.

The switching frequency is controlled by potentiometers which independently vary the length of the relay "open" and "closed" parts of the cycle. The switching action takes a finite time and the component of the field perpendicular to the optical axis is never precisely zero. Consequently, the actual effect on the field of switching the Z-coil current is simultaneously to rotate the field

and change its amplitude. The effect this has on the magnetization of the rubidium vapor depends on how the switching time compares with the precession period of the atoms. This may be important in understanding how changes in the magnitude of the X-coil current effects the waveform of the opacity signal. (You can explore the effect of switching time with the program called "Optical Pumping Simulation" on the Junior Lab PC's - see Appendix A.)

HELMHOLTZ COILS

Helmholtz coils are pairs of identical circular coaxial coils separated by a distance equal to their radius and carrying identical currents. They produce a highly uniform magnetic field over an extended region near their geometrical center given by

$$B_I = \frac{\mu_0 R^2 N I}{[R^2 + (R/2)^2]^{3/2}} = \frac{8\mu_0 N I}{\sqrt{125}R} \tag{8}$$

where R is the radius of the coils in meters, I is the current through the coils in Amperes, N is the number of turns and $\mu_0 = 4\pi \times 10^{-7}$ Wb $A^{-1}m^{-1}$. Remember also that 1 Wb m^{-2}=1 Telsa = 10^4gauss.

1. Vertical (X-axis) Field Coils: These are used to control the vertical component of the magnetic field. Note that the optical axis of the apparatus is aligned within 17° of the earth's magnetic north-south direction. This means that after cancellation of the vertical component of the earth's field the remaining field will be nearly axial.

2. Longitudinal (Z-axis) Field Coils: These are powered and operated by a circuit similar to that used for the vertical coils. Their current is adjusted with the potentiometer under the left hand meter. The longitudinal coils are provided with a toggle switch ("by-pass","relay") which allow them to be connected to an on-off relay. The toggle switch is used to open or close the by-pass connection. The system is put in the automatic relay switching mode by putting the toggle switch in the "relay" position. **Note that in order to access lower currents with the Z-axis current control, a 10-turn, $\sim 1000\Omega$ potentiometer must be used as the jumper.**

3. Lateral (Y-axis) Field Coils: These are used to eliminate any lateral component of the ambient field which results from not having the optical bench perfectly aligned with the magnetic north-south direction.

OVEN HEATER

The vapor cell is in an oven made of plexiglass heated by forced hot air from a blower beneath the table. Turn on the blower, and adjust the Variac for proper temperature. For initial warm-up, use no more than 40 volts, reducing this after five or ten minutes to about 30 volts for a stable oven temperature of $35 - 40°$. **You should turn on the heater at the very beginning of the lab session so that an equilibrium temperature is reached after about 30 minutes.**

EXPERIMENTS

QUANTITIES YOU CAN MEASURE

1. Separation between the magnetic substates of the ground states of the two natural rubidium isotopes as a function of magnetic field strength.

2. The Landè g-factors and their ratio for the ground states of the two isotopes.

3. e/m

4. The relative abundance of the two isotopes.

5. The magnitude and direction of the ambient field.

DEPOLARIZATION BY RF RESONANCE: MEASUREMENT OF THE MAGNETIC MOMENTS OF THE RUBIDIUM ISOTOPES; MEASUREMENT OF THE AMBIENT MAGNETIC FIELD

In this experiment the vapor is continuously pumped, resulting in a high degree of polarization of the atomic angular momenta in the gas traversed by the pumping beam. After about one-tenth of a second of pumping, an equilibrium is reached at which the rate of polarization by pumping of the atoms along the beam equals the rate of depolarization by collisions. At that point the vapor becomes relatively transparent because the number of atoms capable of absorbing the circularly polarized photons becomes constant. The rate of depolarization can then be increased by flooding the vapor with low-energy RF photons tuned to the frequency of the magnetic substate transitions,

$$f = \frac{\Delta E}{h} = \frac{g_F \mu_B B_z}{h} \tag{9}$$

where ΔE is the difference in energy between adjacent magnetic substates. (The frequency required to induce transitions in ^{85}Rb ($i = 5/2$) is approximately 0.5 megahertz per gauss). Photons with the resonant frequency

of a particular isotope induce both upward transitions (absorption) and downward transitions (stimulated emission) among the magnetic substates of the ground electronic state of that isotope. The result is an increase in the absorption of the pumping beam.

The resonant frequencies depend on the magnitude of the total field $|\vec{B}|=(B_x^2 + B_y^2 + B_z^2)$and not just on its Z-axis component. It is left to you to compute the field produced by the Helmholtz coil from measurements of the coil parameters and the current.

The digital oscilloscope will serve as a high resistance voltmeter with the sweep trigger select set on "line". The signal from the differential amplifier is fed to the y-channel (DC) so that it appears as a vertical deflection of the horizontal trace. When you find a resonance, search for the resonance of the other isotope. (Watch out for the effects of harmonics of the fundamental oscillator frequency which occur if the amplitude of the frequency generator is set too high.) The frequency of the signal should be measured with a precision frequency meter. In this part of the experiment you should aim to obtain the following results:

- magnetic moments of the rubidium atoms in their ground state
- precise determination of the ratio of the Landè g-factors of the two isotopes
- the magnitude and direction of the ambient magnetic field

The following is an outline of a possible procedure:

1. Set the Z, Y, and X-coil currents to zero.
2. Search for the resonance frequencies of the two isotopes in the ambient field.
3. Adjust the X-coil current step-by step so as to minimize the resonance frequency (by bucking out the vertical component of the ambient field. Tabulate and plot (in your lab book) the X-current and the two resonance frequencies at each step. Trace the hyperbolic relations of frequency versus current on either side of the minima.
4. With the X current set at the value for the minimum resonance frequencies, adjust the Y-coil current in the same manner, and set it to the value for the new minimum resonance frequencies.
5. Finally, tabulate and plot the Z-coil current and resonance frequencies on both sided of the minimum, and see how low a resonance frequency you can achieve (it should be possible to go as low as 10 kHz).

With the data obtained in this way and the coil dimensions, you will have all the information you need to derive the required results.

ALTERATION OF THE POLARIZATION BY CHANGES OF THE MAGNETIC FIELD

Buck out the vertical and lateral components of the earth's field with the X and Y coils, as above. The Z-coil current can be alternately turned on and off by a relay driven by a multivibrator circuit in the control chassis. The waveforms representing the opacity as a function of time after turn-on and turn-off can be observed and captured on the digital oscilloscope with the opacity signal displayed on one beam, the Z-coil current displayed on the other beam, and the sweep triggered by the relay signal so as to hold the waveform steady on the screen. Precise measurements of the waveforms in the form of amplitude versus time can be made with the horizontal (TIME) and vertical (VOLTAGE) cursors of the digital oscilloscope. (Note that the time constants of the rise and fall of the current in the Helmholtz coil are different.) Record and explain the effects on the waveforms of various changes in the conditions. For example:

1. Change the strength of the field.
2. Change the pumping rate by interposing neutral gray filters in the light beam.
3. Change the density of the rubidium vapor by changing the bulb temperature.

(The time constant of the change in opacity following a sudden change in the magnetic field is determined by two competing factors - the intensity of the pumping beam and the rate of disorientation of the atoms through collisions which enhances the "relaxation" and return of the pumped system to its normal state.)

You should work out the mathematical theory of the competition between pumping and collisional depolarization in order to interpret your results. (The problem is analogous to that of filling a bucket with a leak in the bottom.)

1. Derivation of the Landè-g factors for the two rubidium isotopes, including the effects of the nuclear magnetic moments.
2. Variation of the opacity a) when the field is flipped; b) if the pumping beam were suddenly turned on, and after some time, turned off.
3. Theory of the Helmholtz coils and numerical calculation of the field off axis.

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APPENDIX A - SIMULATION OF THE EFFECTS OF FIELD REVERSAL

The magnetic moment $\vec{m}$ of an ensemble of non-interacting atoms or nuclei under the influence of an external magnetic field $\vec{B}$ can be described by the equations of motion of an angular momentum $\vec{L}$ under the influence of the torque $\vec{m} \times \vec{B}$ where $\vec{m} = \gamma \vec{L}$, and γ is the gyromagnetic ratio. Thus

$$\frac{d\vec{L}}{dt} = \vec{m} \times \vec{B} = \gamma \vec{L} \times \vec{B} \tag{10}$$

In a constant field the motion is gyroscopic precession with a period of $T = \frac{2\pi}{\gamma B}$. To integrate this equation numerically we express the angular moment at $t + \Delta t$ in terms of its value at t by the Taylor expansion

$$\vec{L}(t + \Delta t) = \vec{L}(t) + \frac{d\vec{L}}{dt}(\Delta t) + 1/2 \frac{d^2\vec{L}}{dt^2}(\Delta t)^2 + ... \tag{11}$$

where each of the terms is evaluated at t , and Δt is adjusted at each step so that it is some fixed and very small fraction of T, i.e. so that $\gamma B \Delta t << 1$. In the optical pumping experiment the magnetic moment is due primarily to the valence electron of the rubidium atom, so the gyromagnetic ratio can be expressed in terms of the charge and mass of the electron by the relation $g \frac{e}{2mc}$ where g, the Landè g-factor, is of the order of unity. The calculation is coded in a National Instruments LabVIEW program available on the Junior Lab Server. With that program you can compute the motion of the angular moment under your choice of angular momentum orientation (polar angles theta, phi), initial magnetic field

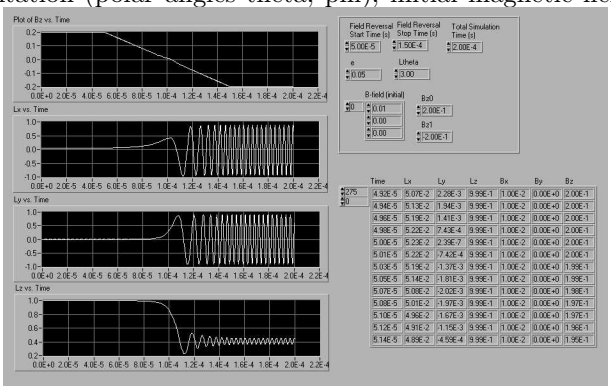

FIG. 7: Example of a computation of the motion of an angular momentum vector under the influence of the torque exerted on the associated magnetic moment by a changing magnetic field.

(B_x, B_y, B_z), final magnetic field (B_x, B_y, B_{z1}), the start and stop times (tt_1, tt_2) of the linear change of B_z, and the duration of the computation ($t_{scale} > tt_2$). An example of the output is shown in Figure . Double click on the icon labeled "Optical Pumping Simulation" and follow the instructions.

OPTICAL PUMPING EQUIPMENT LIST

Model	**Description**	**Source**
	Linear Polarizer	`www.oriel.com`
	∼1 cm Photodiodes	Home-built
	794.7nm filter	www.oriel.com
Lens $f \cong 17.2$ cm	thorlabs.com	
	Lens $f \cong 23.3$ cm	thorlabs.com
	Quarter Waveplate	thorlabs.com
	Variable Attenuator	Home-built
MDSS116-TC-A	Thermometer	`www.omega.com`
HP 200CD	Oscillator	`www.hp.com`
Tektronix CMC250	Frequency Counter	`www.tektronix.com`
Staco 3PN1010	Variac	`www.stacoenergy.com`
	122cm Optical Rail	Home-built
	Optical Components	Homebuilt
	Rb Lamp	Home-built
	Rb Lamp Power	Home-built
	Rb absorption cell	Home-built
	Helmholtz Coils	Home-built
	Current Supply	Home-built
	RF Coils	Home-built