Optical-Pumping Method

1 *Purpose*

The object of this experiment is to measure the energy splitting of the hyperfine structure of the lowest energy state of rubidium which is subjected to a uniform magnetic field whose magnitude can be determined by other means. From the method called "optical pumping", you will deduce the frequency of the rf-transitions in this magnetic dipole interaction which will then allow you to determine the g-factor of the resultant magnetic moment and the magnitude of the nuclear spin. You will note that this experiment requires the conservation of both energy (in the resonance phenomenon) and angular momentum (in the absorption of photon quanta) in order to proceed.

The Nobel Prize in Physics was awarded to Alfred Kastler for his pioneering work on this highly important experimental method. Kastler (with the help of Jean Brossel) was the first to propose a successful optical method to investigate rf resonances in atoms. He believed that selected magnetic sublevels could be excited from higher lying energy levels using polarized light having the correct resonance frequency. In 1952, Kastler performed an experiment that confirmed the practicality of his recommendation and the validity of his theory. Other important developments that followed *as a result* of Kastler's work include such things as lasers, sensitive magnetometers, and atomic clocks.

2 *Theoretical background*

2.1 Thermal population distribution

The atoms of some material at a specific temperature, T, are usually distributed amongst a number of different energy states. Under ordinary conditions, the higher the energy level, the smaller the number of atoms in each level. Thus, the lowest energy state is generally populated to the greatest amount. Such a distribution is referred to as a thermal distribution. The relative population of any two (negative) energy levels, E_1 and E_2 with $E_1 < E_2$, is given by the Boltzmann factor such that

$$\frac{N_2}{N_1} = e^{-(E_2-E_1)/kT} \,. \tag{1}$$

This relation yields the fractional difference in population, $\frac{\Delta N}{N} = 1 - \frac{N_2}{N_1}$ given approximately by

$$\frac{\Delta N}{N} \approx \frac{E_2 - E_1}{kT} \tag{2}$$

when the energy kT is much larger than the energy difference between levels. Of course, in the absence of an external field, all of the *magnetic* substates are equally populated, since they all have the same energy. However, for fields on the order of a Gauss, and for temperatures typical of those used in this experiment, you should verify that the fractional excess population is less than 0.1 ppm in level-1. Thus, ground-state rubidium atoms indeed reside with equal populations throughout all of its magnetic substates.

2.2 Example: A simple 1-electron system

Under the right conditions, it is possible to cause the atoms to have a different distribution. When a non-thermal distribution is achieved by using a source of light, the process is then called "optical pumping". In order to see the essence of this scheme, let us first describe a simple energy level system (with no hyperfine structure as described later in this writeup) for a sample of gas atoms which has a $^2\mathrm{S}_{1/2}$ ground state and a $^2\mathrm{P}_{1/2}$ excited state. Assume in this case that the atoms in the sample are all found in the ground state with its magnetic sublevels equally populated. In a weak magnetic field, the energy level diagram will look something like that shown in Fig. 1.

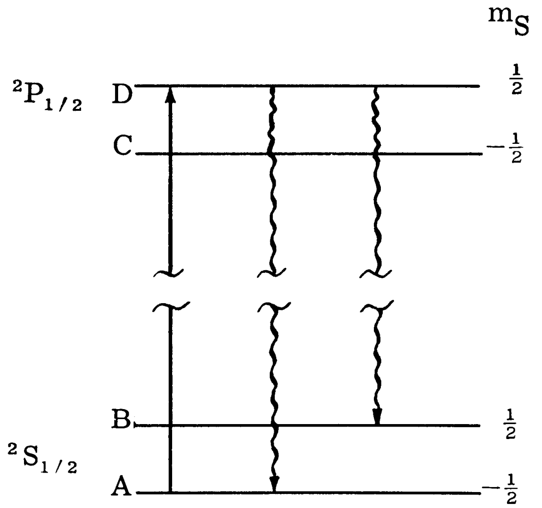


Figure 1: Hypothetical energy level diagram showing each fine-structure term split into doublets by the magnetic interaction. The optical absorption of a photon polarized in the σ^+ state, shown with state-A → state-D, corresponds to +1 change in the magnetic quantum number ($\Delta m_S = +1$). Note, however, that spontaneous emission has equal probability of ending with states A or B. Repeated absorption-emissions would eventually populate state B above the thermal-equilibrium value.

[Note: The theory section of the "Zeeman Effect" write-up reviews the rules for "Russell-Saunders coupling." This first-order energy coupling (or so-called spin-orbit interaction) yields the fine-structure in the energy level diagram, i.e. the primary energy separation between the $^2\mathrm{P}_{1/2}$ and the $^2\mathrm{S}_{1/2}$ states when the magnetic interaction is absent. Also in the "Zeeman Effect" write-up is a good description of the vector model for angular momentum addition.]

In the presence of a magnetic field, the degeneracy between the m_s sublevels is lifted. The sublevel energies acquire an additional term due to the spin's orientation relative to the direction of the magnetic field, $\vec{\boldsymbol{B}}_0$:

$$E(\text{magnetic}) = g_s \mu_B B_0 m_s \tag{3}$$

where $\mu_B = e\hbar/2m_e$ is the Bohr magneton and g_s is the electron's Lande g-factor whose tiny difference from exactly 2.0 (as predicted by Dirac) is due to fluctuations in the electromagnetic vacuum. The quantity, m_s, is the magnetic quantum number which can have a value of either $+\frac{1}{2}$ or $-\frac{1}{2}$, depending on the spin's alignment with the direction of the magnetic field.

Now assume that some resonant optical radiation impinges on the atoms in the sample, and the energy of that radiation is absorbed as indicated by the upward pointing broken arrow. The selection rules for the absorption of electric dipole radiation into the excited state from the ground state are $\Delta\ell = \pm 1$ and $\Delta m_s = 0, \pm 1$. The first selection rule is valid because the transition is $^2\mathrm{S}_{1/2} \rightarrow {}^2\mathrm{P}_{1/2}$ with $\Delta\ell = +1$. As for the second rule, assume that the impinging radiation is circularly polarized. This rule indicates that $\Delta m_s = +1$ or $\Delta m_s = -1$, but not both. Which one is valid depends on the the direction of the magnetic field relative to the direction of light propagation as well as the direction of circular polarization. If the angular momentum of the photon (according to the electric field's rotation by the right-hand rule) is along the direction of propagation of the light (i.e. the direction of the photon's momentum), the light is said to be right-circularly polarized and is given the notation σ^+. This polarization state produces $\Delta m_s = +1$ transitions. Likewise, left-circularly polarized σ^- light will produce $\Delta m_s = -1$ transitions.

Figure 1 illustrates the absorption of σ^+ light which *only* allows a transition from state-A to state-D. Assuming no disorientation by collisions occurs during the lifetime of about 10^{-8} seconds for this excited state, the atom will fluoresce from state-D to state-A and state-B with equal probability. Thus, some of those atoms leaving state-A do not return to state-A, but end up in state-B. Without any means of transferring atoms from state-B back to state-A, the ensemble of atoms in the sample will *all* eventually end up in the higher energy state-B, thus producing a non-thermal population distribution.

If one is observing the intensity of the light transmitted through the sample, one initially notes the existence of absorption by the reduction of the light intensity, but as the state-B becomes fully populated, the gas becomes transparent and the light intensity through the gas is at a maximum. In a real system, state-B may not become fully populated because the final distribution will depend on such parameters as the intensity of the pumping light (see Sec. 3.1), the relative transition probabilities of multiple allowed states (which might compete for sublevels), and the relaxation rates through various internal-gas or wall collisions.

2.3 Hyperfine structure interaction

The main features of atomic spectra for atoms with one optically-active electron are associated with the interaction of the spin magnetic moment of that electron and its orbital magnetic moment. These features have become known as the "fine structure" of the atomic spectra because they showed up first with improved resolution of optical spectrometers. One can show that the interaction responsible for the fine-structure energy shift is given by

$$\Delta E(\mathrm{fs}) = a\mathbf{L} \cdot \mathbf{S} \tag{4}$$

where **L** and **S** are the orbital and spin angular momentum quanta, respectively, and the fine-structure coupling constant a is given by

$$a \propto \frac{1}{r}\frac{dV(r)}{dr} \sim \mu_B^2 \left\langle \frac{1}{r^3} \right\rangle . \tag{5}$$

The function $V(r)$ is the electrostatic potential of the nuclear charge as it interacts with the electrons orbiting the nucleus. The spatial average (denoted by the angle brackets) is taken using the electronic wave-function ψ_e.

As spectrometer resolution was further improved, a still finer structure was observed, now referred to as the "hyperfine structure" of the atomic spectra. When the nucleus is given the added property of quantized angular momentum, **I**, we see that a nuclear magnetic moment, $\vec{\boldsymbol{\mu}}_I$, will exist. Its interaction with the magnetic field produced by the atomic electrons at the position of the nucleus is given by

$$\Delta E(\text{hfs}) = A\mathbf{I}\cdot\mathbf{J} \tag{6}$$

where $\mathbf{J}$ is the sum of $\mathbf{L}$ and $\mathbf{S}$ and the hyperfine-structure coupling constant A depends on the nuclear magneton but is otherwise similarly dependent on r as the fine-structure interaction above:

$$A \propto |\psi_e(0)|^2 \sim \mu_n \mu_{_B} \left\langle \frac{1}{r^3} \right\rangle . \tag{7}$$

In this case, r represents the electron's radial distance from an assumed "point" dipole located at the center of the nucleus. The nuclear magneton $\mu_n = \mu_{_B} m_e/m_p$ is 1836 times smaller than the Bohr magneton. Thus, $\Delta E(\text{hfs})$ is typically three orders of magnitude smaller than $\Delta E(\text{fs})$. In weak external magnetic fields, the strong coupling of angular momenta, $\mathbf{I}$ and $\mathbf{J}$, yields another quantum mechanical angular momentum $\mathbf{F}$ which is the vector sum $\mathbf{I}+\mathbf{J}$. Thus, $\mathbf{F}$ is quantized with values ranging from $I+J$ to $|I-J|$. It should be noted that transitions between levels of different F, which are referred to as the hyperfine transitions, will involve absorption or emission of magnetic dipole radiation (to change direction of a nuclear magnetic moment) with $\Delta F = 0, \pm 1$ only. Likewise, transitions between different $m_{_F}$ levels with F remaining constant comprise the Zeeman transitions (which are also due to magnetic dipole interactions), but now with $\Delta m_{_F} = 0, \pm 1$ only.

2.4 *g*-Factor calculations

Before proceeding to the rubidium experiment, let us first review the rules for computing the g-factors associated with a magnetic moment that depends on the coupling of the spin angular momentum $\vec{\boldsymbol{S}} = \mathbf{S}\hbar$ and the orbital angular momentum $\vec{\boldsymbol{L}} = \mathbf{L}\hbar$. The associated magnetic moments are

$$\begin{aligned} \vec{\boldsymbol{\mu}}_{_S} &= -g_s \cdot \frac{\mu_{_B}}{\hbar}\vec{\boldsymbol{S}} && (8) \\ \vec{\boldsymbol{\mu}}_{_L} &= -g_\ell \cdot \frac{\mu_{_B}}{\hbar}\vec{\boldsymbol{L}} && (9) \end{aligned}$$

where the quantum mechanical values for the angular momenta are

$$\begin{aligned} |\vec{\boldsymbol{S}}| &= \sqrt{S(S+1)}\hbar && (10) \\ |\vec{\boldsymbol{L}}| &= \sqrt{L(L+1)}\hbar\,. && (11) \end{aligned}$$

The above magnetic moments add vectorially to yield magnetic moment, $\vec{\boldsymbol{\mu}}$, which precesses around an axis parallel to the resultant angular momentum, $\mathbf{J} = \mathbf{L} + \mathbf{S}$ with quantum-mechanical value $\sqrt{J(J+1)}\hbar$. However, the magnetic behavior of this system depends only on $\vec{\boldsymbol{\mu}}_{_J}$, the component of $\vec{\boldsymbol{\mu}}$ in the direction of $\vec{\boldsymbol{J}} = \mathbf{J}\hbar$ where

$$\vec{\boldsymbol{\mu}}_{_J} = -g_{_J} \cdot \frac{\mu_{_B}}{\hbar}\vec{\boldsymbol{J}}\,. \tag{12}$$

Figure 2 illustrates the vector addition of $\mathbf{L}$ and $\mathbf{S}$ as well as the associated magnetic moments. The component, $\mu_{_J}$, is given by the relation

$$\mu_{_J} = \mu_{_L}\cos\theta_{_{LJ}} + \mu_{_S}\cos\theta_{_{SJ}} \tag{13}$$

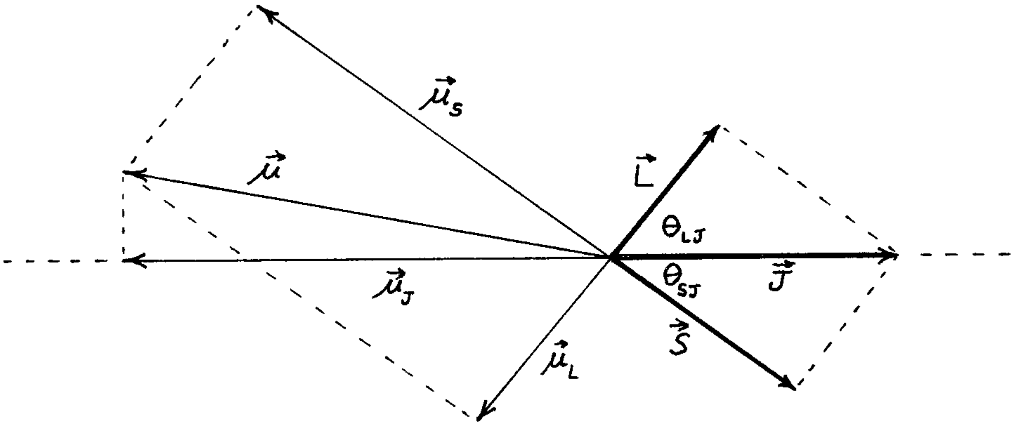


Figure 2: Origin of magnetic moment $\vec{\mu}_J$. It should be noted that the direction of the angular momentum vectors is opposite to that of the corresponding magnetic moments.

where the law of cosines yields

$$\begin{aligned} L^2 &= S^2 + J^2 - 2SJ\cos\theta_{SJ} && (14) \\ S^2 &= L^2 + J^2 - 2LJ\cos\theta_{LJ}\,. && (15) \end{aligned}$$

Upon substituting for the magnetic moments given in (8), (9) and (12) , one obtains

$$g_J J = g_L L\cos\theta_{LJ} + g_S S\cos\theta_{SJ}\,. \tag{16}$$

Finally, upon substituting for the values of the cosines in (14) and (15) into (16), using the fact that $g_\ell = 1$ and $g_s \approx 2$, and solving for the g-factor g_J, one obtains

$$g_J = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}\,. \tag{17}$$

Following the same procedure for the hyperfine structure using

$$\vec{\boldsymbol{\mu}}_I = -g_I \cdot \frac{\mu_n}{\hbar}\vec{\boldsymbol{I}} \tag{18}$$

for the magnetic moment associated with nuclear spin angular momentum $\vec{\boldsymbol{I}} = \mathbf{I}\hbar$, you should be able to show that the hyperfine g-factor g_F is given by

$$g_F = g_J\frac{F(F+1) + J(J+1) - I(I+1)}{2F(F+1)} - g_I\left(\frac{\mu_n}{\mu_B}\right)\frac{F(F+1) + I(I+1) - J(J+1)}{2F(F+1)} \tag{19}$$

where the second term in the above is often ignored since μ_n is three orders of magnitude smaller than μ_B:

$$\frac{\mu_n}{\mu_B} = \frac{m_e}{m_p}\,. \tag{20}$$

3 The rubidium experiment

For this experiment, a special apparatus has been constructed whose purpose is to be compact and self-contained, but its components can not be readily viewed. The apparatus is housed inside of a phenolic tube, which also gives it some thermal isolation from the environment. As shown in Fig. 3, the phenolic tube contains the Rb-spectral lamp, a lens, an interference filter, a circular polarizer, the Rb-absorption cell, and a photo-diode detector. The converging lens is needed in order to collect the diverging rays from the spectral lamp and produce a parallel beam of light that propagates along the axis of the tube, through the absorption cell, and onto the photo-diode detector. A mask in the form of a thin disk with a small hole is placed directly in front of the Rb lamp. It prevents light reflected by the concave mirror in back of the lamp from entering the absorption cell. Since most of this reflected light would not be parallel to the z-axis of the tube (and therefore not be parallel to the $\vec{B}_0$ field), it would cause a broadening of the resonance which is observed when applying the perpendicular rf magnetic field, $\vec{B}_1$. Although the mask cuts down on the intensity of the transmitted light being detected, the linewidth of the resonance is narrowed considerably. In order to eliminate the D_2 spectral component in this light beam, an interference filter which is strongly peaked at 794.8 nm (the D_1 line) follows the lens. Next, a linear polarizer and quarter-wave plate are mounted in the light path, immediately before the absorption cell. This combination serves to circularly polarize the light from the Rb-lamp. The light coming out of the linear polarizer (which is linearly polarized) is set at a 45° relative to the slow and fast axes of the quarter-wave plate; then the relative phases of the fast and slow components of the light's electric vector change by 90° in order to produce circularly polarized light. Finally, a 5-cm diameter, 7.5-cm long absorption cell follows, containing the tiny amount of purified rubidium metal. In order to increase the degree of polarization of the optical-pumped sample, 50 Torr of neon buffer gas is included inside the absorption cell. In addition, the cell walls are prepared with a thin coating of tetracontane which is a long-chain saturated hydrocarbon. Such films have been found to reduce the wall-relaxation rate by more than a factor of five.

In order to produce the time dependence in the polarization of the sample, a solenoid is wound around the phenolic tube such that the axis of the $\vec{B}_0$-modulation field is co-linear with the direction of the pumping light. In order to increase the essential uniformity of this field, the coils are made about twice the length of the absorption cell. *It is crucial that the* $\vec{B}_0$*-modulation field be made parallel to the earth's field so that the two can be added like scalars.* The other method of treating this problem (which we do not use) is to buck out the earth's field using special Helmholtz coils, known for their high-degree of uniformity. To complete the configuration that yields the time dependence of the sample polarization, another set of modulation coils are wound outside of the $\vec{B}_0$ solenoid (windings not shown in Fig. 3) in order to produce a perpendicular $\vec{B}_1$ rf-field that will be used to disorient the polarization of the sample.

In this particular experiment, the rubidium metal, which is sealed into the glass cell, should be heated above the metal's 38.5°C melting point. At room temperature, the absorption cell should contain enough rubidium vapor in order to get a weak resonance signal. The signal will improve a lot after allowing the lamp to warm the cell: about an hour of warm-up is sufficient. The large aluminum housing that holds the cell also insulates it thermally.

There are two common isotopes that are present in the resulting vapor, ^{85}Rb with nuclear spin $I = 5/2$ and ^{87}Rb with nuclear spin $I = 3/2$, whose relative abundances are $72\% : 28\%$ respectively. When this vapor cell is placed in a weak magnetic field, the Zeeman splitting of the hyperfine structure is created. A schematic energy-level diagram for the single optically-active electron in

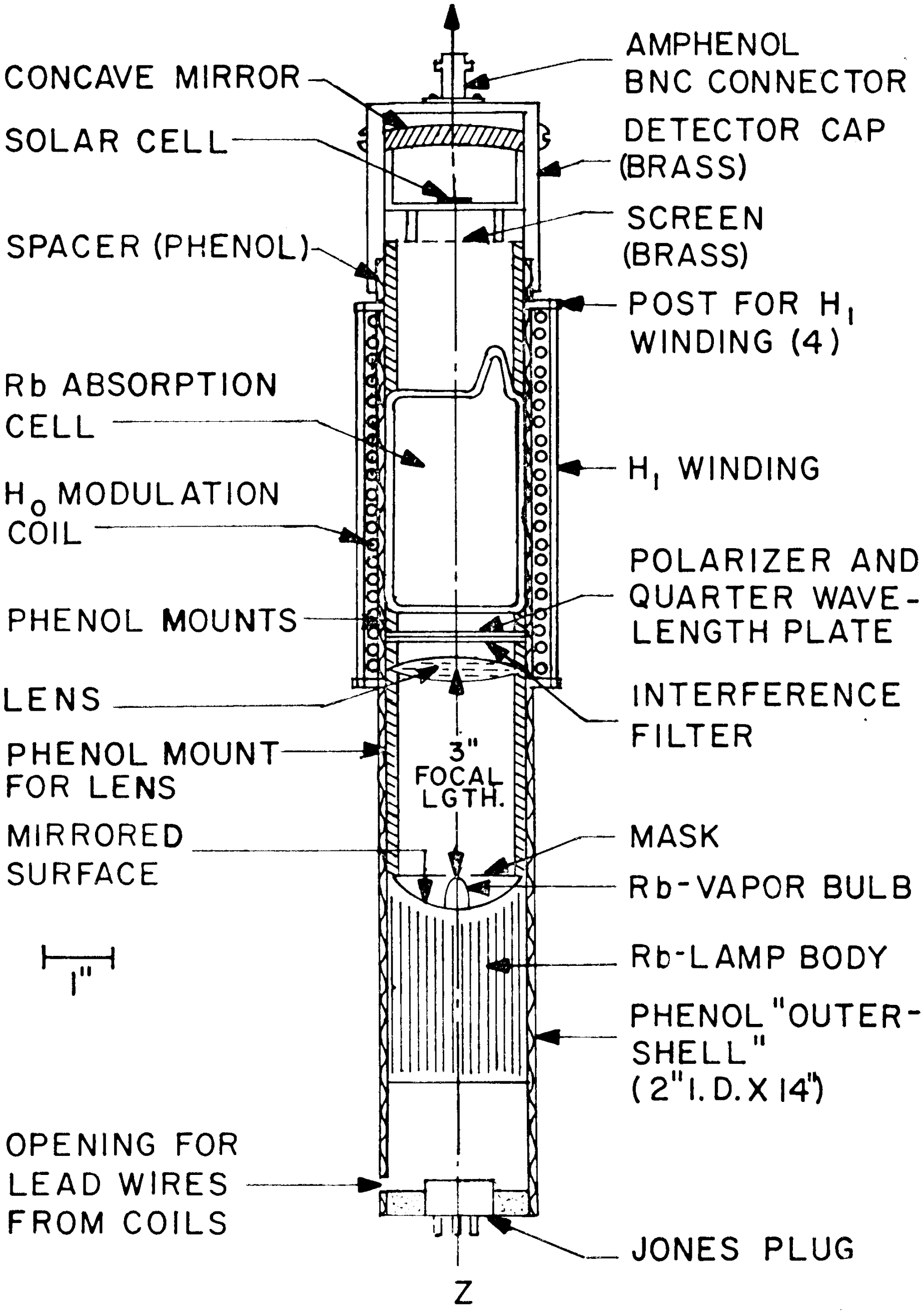


Figure 3: Experimental arrangement of optical components in a phenolic tube that comprise the optical pumping system. The polarizer and quarter-wave plate are mounted together, but the polarizer must be closer to the Rb-vapor lamp.

^{87}Rb is shown in Fig. 4. Note the relative energy separations between the fine structure splitting,

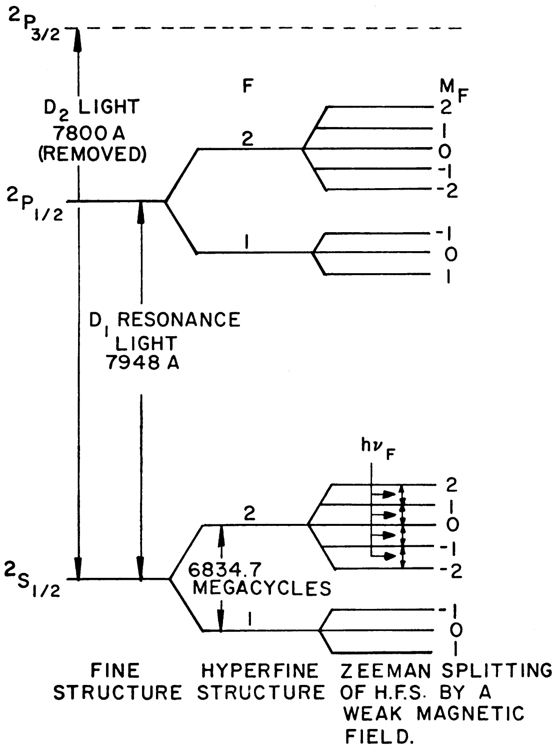


Figure 4: A diagram of the energy levels of ^{87}Rb with $I = 3/2$.

the hyperfine-structure splitting, and the Zeeman splitting. These are clearly not shown to scale; if they were, they would then be 1,500,000,000 : 27,000 : 1 in relative proportion.

For ^{85}Rb, the nuclear spin of 5/2 generates hyperfine levels $F = 2$ and $F = 3$. Using the expected magnetic interaction in the hyperfine Zeeman structure

$$\Delta E(\text{magnetic}) = h\nu_F = g_F \mu_B B_0 \Delta m_F \ , \tag{21}$$

you should be able to show that the energy differences arising from the $\Delta m_F = 1$ transitions using ^{85}Rb instead of ^{87}Rb are 2/3 as large.

3.1 Time dependence of optical pumping

Atoms in the fully-pumped state tend to become disoriented mainly because of collisions with the glass walls. The fully-pumped state is called "fully oriented" because the m sublevel is maximized making the magnetic moment greatest along the direction of the magnetic field. The rate of disorientation is called the "relaxation rate." On the other hand, a disoriented atom becomes oriented through optical pumping, and this process leads to a competing "orientation rate." Both processes determine the overall rate at which the gas of atoms reaches its maximum orientation and the steady-state value of maximum orientation that can be sustained with the pumping light on. The time constants of the overall process can be studied by observing the oscilloscope trace, similar to that shown in Fig. 5, as the sample proceeds from the completely *disoriented* state to the maximally-pumped state. If one can control the intensity of the pumping light, it becomes possible

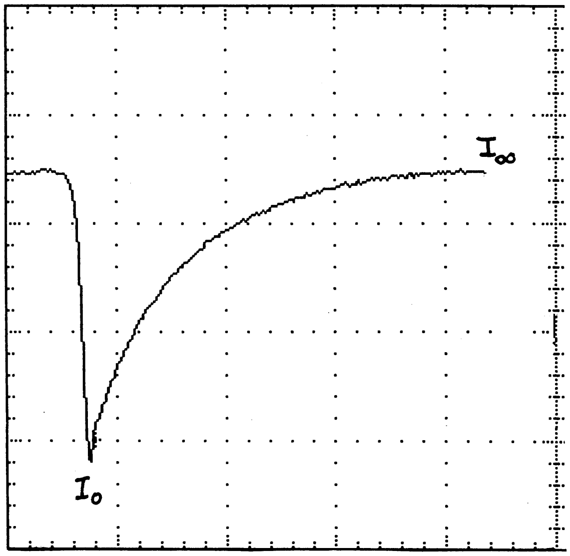


Figure 5: Trace of the transmitted light intensity versus time. The level marked I_∞ represents the fully-pumped state and the level marked I_0 is the initial intensity after the disturbance to the fully-pumped state. The horizontal scale is 2.5 ms per major division.

to extract the disorientation rate alone from such traces, as will be evident from the discussion below. Unfortunately, for our old optical pumping system, the pumping light intensity is fixed.

For the sake of simplicity, the following discussion of the two rates assumes that there is only the ^{87}Rb isotope in the cell. First we must prepare the sample. Let D_1 radiation at 794.8 nm be incident on the cell, causing absorption from $^2S_{1/2} \rightarrow {}^2P_{1/2}$. If the light has σ^+ polarization, then in the absence of collisions, all the atoms will end up in the $F = 2$, $m_F = 2$, sublevel, as described earlier. This represents the fully pumped state which can no longer absorb electric dipole radiation at the D_1 wavelength. It is important that D_2 light must not be available, or else an escape channel is opened to the $^2P_{3/2}$, $F = 3$, $m_F = 3$ excited state, and atoms in this state experience a higher relaxation rate by collisions with the background vapor.

Now, we apply an rf magnetic field $\vec{\boldsymbol{B}}_1$ to the sample at right angles to the weak dc $\vec{\boldsymbol{B}}_0$ field aligned along the axis of the phenolic tube shown in Fig. 3. Further assume that the frequency of the $\vec{\boldsymbol{B}}_1$ field is close, but slightly above ν_F where $h\nu_F$ represents the energy difference between adjacent magnetic sublevels in the $^2S_{1/2}$, $F = 2$ ground state. By slowly ramping up B_0, the $\vec{\boldsymbol{B}}_1$ field can become resonant to this energy spacing and thus induce rapid absorption or stimulated emission by induced magnetic dipole transitions. This process induces a rapid de-orientation of the atoms, much faster than through collisions, since it tends to equalize the population in the Zeeman sublevels and destroy the original magnetic orientation corresponding to the sample being in the fully-pumped ground state.

The trace was made in Fig. 5 using the same ramp to generate the time sweep for the oscilloscope's horizontal scale as used to sweep the B_0 field. The slope of the initial sharp drop in intensity, from the I_∞ level to I_0 (from left to right), depends on the degree of homogeneity of the B_0 field across the sample cell. If the field were completely homogeneous, this edge would be exactly vertical. As it is, the atoms in the cell become disoriented at different locations throughout the sample volume, causing the initial non-vertical slope.

As soon as all parts of the sample have passed through resonance with the $\vec{\boldsymbol{B}}_1$ field, the pumping process becomes evident as the light transmitted through the sample begins to increase in intensity. In effect, we assume that the pumping process consists essentially of raising atoms indiscriminately from all the other ground-state sublevels to the $m_F = 2$ ground sublevel. Let dn/dt be the rate of change of the $m_F = 2$ ground-state population, n, and let dN/dt be the rate of change of population, N, for *all other* ground-state sublevels ($m_F \neq 2$). Further, define $W_d dt$ to be the probability for downward transitions from the $m_F = 2$ level (mostly via collisions), and define $W_u dt$ to be the probability for upward transitions to the $m_F = 2$ level (via the pumping light). As for our initial conditions at $t = 0$ when $I = I_0$ (the lowest intensity level of the transmitted light), let $n = n_0$ (the initial population of the $m_F = 2$ sublevel) and $N = N_0$ (the initial population of all other ground-state sublevels). The rate equations for the time-dependent values of these populations becomes

$$\frac{dN}{dt} = nW_d - NW_u \tag{22}$$

$$\frac{dn}{dt} = NW_u - nW_d \,. \tag{23}$$

The solutions to these two rate equations consistent with initial conditions are

$$N = N_0 - C(1 - e^{-t/\tau}) \tag{24}$$

$$n = n_0 + C(1 - e^{-t/\tau}) \tag{25}$$

where $\tau \equiv (W_u + W_d)^{-1}$ and $C = (N_0 W_u - n_0 W_d)/(W_u + W_d)$.

Finally, if one assumes that the transmitted intensity is proportional to the number of excess atoms in the $m_F = +2$ ground sublevel, according to $I = \alpha(n - N)$, it follows that

$$I = I_\infty - \alpha C e^{-t/\tau} \tag{26}$$

where $\alpha C = I_\infty - I_0$ is the amount of light lost at full disorientation. The above equation is in qualitative agreement with observed results. At $t = 0$, when the sample is completely disoriented, I is a minimum. Thereafter, as the pumping proceeds, I increases exponentially to the limit, I_∞.

Note also: if the light intensity is reduced, W_u must reduce (because of fewer photons available to make upward transitions), and thus C would approach zero. However, for pumping to occur, C must be positive which yields

$$W_u \geq \frac{n_0}{N_0} W_d \,. \tag{27}$$

Let $(1/\tau)_{\min}$ be the rate measured at minimum pumping light. Since $1/\tau \equiv W_u + W_d$, it then follows that

$$\left(\frac{1}{\tau}\right)_{\min} \rightarrow \left(\frac{n_0}{N_0} + 1\right) W_d \tag{28}$$

where W_d^{-1} is a measure of the relaxation time by all causes *from* the fully pumped state.

For ^{87}Rb, n_0/N_0 is equal to 1/7, assuming equal populations in all eight ground-state sublevels. Thus, in the limit as the pumping light intensity is reduced, the rate back to the pumped state becomes $\tau_{\min}(87) = (7/8)W_d^{-1}$. And for ^{85}Rb, n_0/N_0 is equal to 1/11, so $\tau_{\min}(85) = (11/12)W_d^{-1}$. This suggests that the rate from a fully disoriented sample towards maximally pumped one should be slightly quicker for the ^{87}Rb atoms than for the ^{85}Rb atoms, assuming that the processes that cause relaxation do not depend on the isotope.

The quantity τ can be determined from the initial slope of the curve in Fig 5, at the onset of resumed optical pumping, where

$$\frac{dI}{dt} = \frac{I_\infty - I_0}{\tau} \,. \tag{29}$$

You will study these phenomena in section 4.4.

4 *Procedure*

In this experiment you will determine the *g*-factor for the ground state of the two isotopes of rubidium, ^{85}Rb and ^{87}Rb. You will investigate the time constant τ for pumping the Rb atoms into the highest Zeeman (magnetic) sublevel of the ground state under two experimental conditions: 1. Equalizing the populations of the ground state sublevels by passing through the resonance condition; 2. completely inverting the ground state sublevels by reversing the magnetic field. You will also estimate the field inhomogeneity across the Rb cell, expressed as so many ppm/cm.

4.1 Preliminary procedure

A diagram of the setup is shown in Fig. 6. Turn on all the electronics. The power supply for the Rb lamp should already be on; the resonance signal does not achieve full intensity until the lamp has been on for an hour or so. The power switch for the ADA400A preamp power supply is on the back of the black box. Other equipment settings follow.

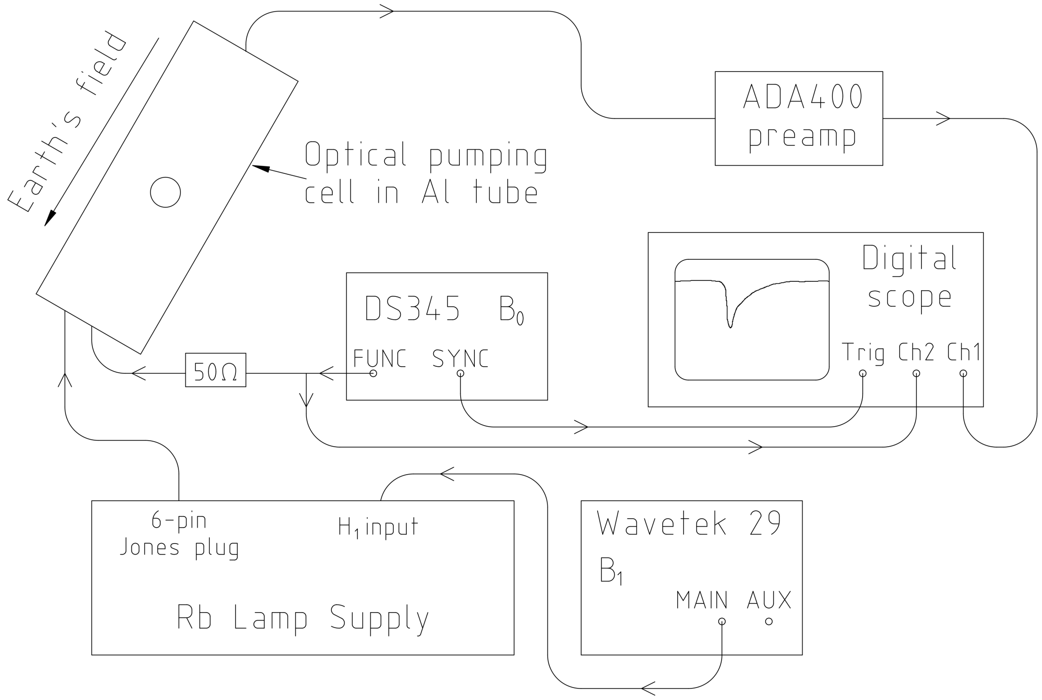


Figure 6: Setup of the optical pumping experiment apparatus.

Rb lamp power supply

Turn on the Power switch, and then after the current comes up turn on the Standby switch.

Current should read 22–25 mA.

ADA400A preamp

Signal to +input, AC coupled, −input switch set to ground;

Gain = 100;

3 kHz upper bandwidth;

Offset OFF;

Output (from black box/power supply) goes to digital scope, Ch1.

DS345 function generator (this generator provides the sweep of the B_0 field)

Freq. = 50.000 Hz;

Amplitude = 2.00 V(olts) pk-pk; (To change amplitude press the AMPL button, enter the desired voltage and then press the Vpp button. This is the general scheme for changing the value of any parameter on this unit; press the button for the desired parameter, enter the desired numerical value, then press the button for the desired units.)

Offset = 0.00 V;

Waveform: ramp, positive slope (shown in Fig. 6);

Output goes to apparatus and to scope, Ch2. Aux out goes to trigger input on digital scope.

Wavetek 29 function generator (this generator provides the B_1 resonance field)

Freq. ≈ 220 kHz; (To change the frequency, use the FIELD buttons to highlight the frequency number and then use UNITS to the desired precision and rotate the knob to the desired value, or enter the value directly from the keypad, ending with the units—like on the DS345.)

Amplitude = 2.0 V pk-pk;

Output "Main out" goes to apparatus; "Aux. out" goes to Fluke frequency meter;

Set OUTPUT to ON.

Tektronix digital scope

Horizontal: 5 msec. per division;

Vertical: Ch1, 20 mV per division, Ch2, 1 V per division.;

Trigger source: Ext., Use a minimum of a 500 mV trigger level;

Cursors: OFF;

averaging feature: OFF.

Before attempting to observe a signal, make sure that aluminum cylinder holding the apparatus is aligned parallel to the earth's field. A compass/tiltmeter is available in the lab to indicate the direction of the earth's field. The tiltmeter should not be left close to the apparatus, as the magnetic fields from the needles will distort the field inside the apparatus resulting in a distorted output signal.

Having set the equipment as indicated above, you should see a signal something like that in Fig. 7. If you do not see anything like the dip in the Ch1 signal, adjust the frequency of the Wavetek generator between 200 and 280 kHz. This generator provides the B_1 (referred to as H_1 in Fig. 3) signal which disorients the polarization upon passing through the resonance condition. If you still don't see anything, make sure all the equipment is on, and check all of the above settings. If you still don't see a signal, consult with TA, Professor or lab manager.

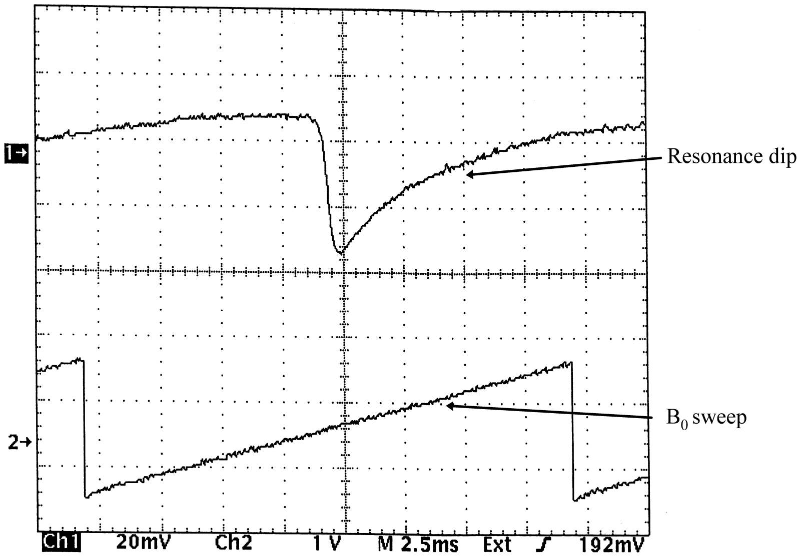


Figure 7: Initial signal from the optical pumping experiment. The resonance dip shows the effect of disorienting the polarization of the Rb atoms leading to an increase in the absorption of the light. As optical pumping proceeds, the cell becomes more transparent.

To get a more stable pattern on the scope, you can display the average of a number of sweeps. To activate this feature, press the ACQUIRE button, select Average and set the number of sweeps to be averaged with the knob at the upper left of the control panel. Averaging just 2 or 4 sweeps will significantly reduce the noise and stabilize the trace while still allowing for a fairly fast response time. To turn off the Average feature, press the Sample button.

If you would like at anytime to generate a printout of what is on the scope screen, just push the HARDCOPY button on the scope and the printer underneath the scope will print the screen. To get a less cluttered printout, press the REMOVE MENU button to the lower right of the screen.

4.2 Measurements to determine g_F

The first set of measurements will be to determine the resonant frequency, f_{res}, for the B_1 signal. Once this frequency is determined and the static B_0 field, i.e., the earth's field, is measured, one can derive g_F using Eq. (21). (B_0 is the same as H_0 in Fig. 3.) The simplest way to proceed would be to measure the frequency of B_1 at the zero crossing of the B_0 sweep field. But this method would provide only one measurement from which to derive g_F. A better method is to introduce a series of offsets in B_0, measure f_{res} at each offset, and then derive the frequency at zero offset from a least squares fit of the data. We shall follow this method to determine g_F for both isotopes of rubidium. We will also be able to determine the offset necessary to cancel the earth's field altogether, since from Eq. (21) one can see that $f_{res} = 0$ when $B_0 = 0$.

After getting a signal like that in Fig. 7 on the scope, turn on the scope cursors (press CURSOR button) and select the vertical cursors. Move the cursors by rotating the knob at the upper left of the control panel. Select the cursor being moved (solid one) with the TOGGLE button to the left of the knob. Set the left cursor just on the vertical edge of the ramp waveform, as in Fig. 8. Make sure that the frequency of the DS345 is *exactly* 50 Hz. Set the right cursor at $\Delta = 10.0$ ms (milliseconds). This is just 1/2 the period of the B_0 sweep waveform and is therefore the zero crossing of this waveform when there is no offset.

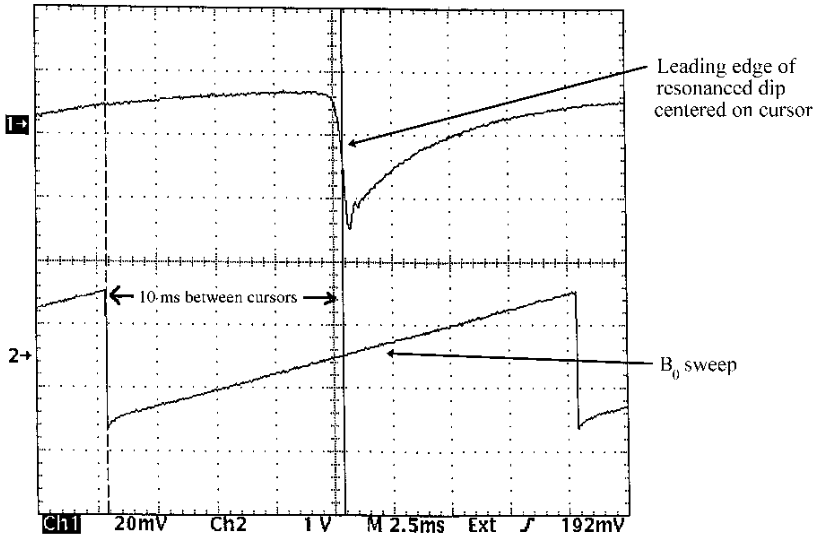


Figure 8: Scope setup used to find B_0. Note that cursors are set to span the range from the beginning of the sweep to the exact midpoint (10 ms). The frequency of B_1 is adjusted to position the dip at the midpoint cursor.

Check that the OFFSET of the DS345 generator is set to 0. Adjust the frequency of the B_1 generator until the leading edge of the dip is centered on the right cursor as in Fig. 8. Note the frequency of B_1; it should be approximately 220–250 kHz. To see how reproducible this measurement is, you may want to move the dip away from the cursor by changing the frequency and then back to where the leading edge is again centered on the cursor. You can get some idea of the uncertainty by repeating this process several times. You should get at least three significant figures on your frequency measurements; for fine tuning, the frequency increment should be 0.1 kHz (or smaller). Check that the time interval between the cursors is still 10 milliseconds. It should remain at 10 milliseconds for this entire set of measurements.

Now introduce an offset into B_0 by setting the offset voltage on the DS345 generator to 0.1 volt. Adjust the frequency of B_1 until the leading edge of the dip is again centered on the right cursor. Again note the frequency. Repeat this process for a series of offsets between −3.00 volts and +1.00

volts. When you analyze your data, perform a (linear) least squares fit for f_{res} vs. V_{offset} to obtain the value of f_{res} at zero offset. This will be the resonant frequency in the earth's field. You will measure this field using the Bell gaussmeter at the end of the experiment.

As you obtain the data, make a plot in order to obtain the offset at $f_{res} = 0$. This will be useful later when measuring the relaxation times, as it will give the offset necessary to null the earth's field.

Set the B_0 offset to zero. Adjust the frequency of B_1 to about 330 kHz. You should again see a dip similar to the one you observed at 220 kHz with no offset. The dip at 330 kHz is smaller as it is due to the ^{87}Rb isotope which has $\approx 1/3$rd the abundance of the ^{85}Rb isotope. You may want to rescale the vertical gain in order to see the resonance more clearly, and take advantage of the averaging feature of the digital scope to clean up the trace. Make sure the time interval between the cursors is still 10 milliseconds and the B_0 frequency is still set at 50 Hz. Now repeat the process of introducing a series of offsets, centering the leading edge of the dip, and noting the frequency, just as for the ^{85}Rb isotope. Again, as part of your analysis, perform a fit for these data to determine the resonant frequency B_1 in the earth's field and the offset necessary to null the earth's field.

4.3 Sensitivity to stray fields

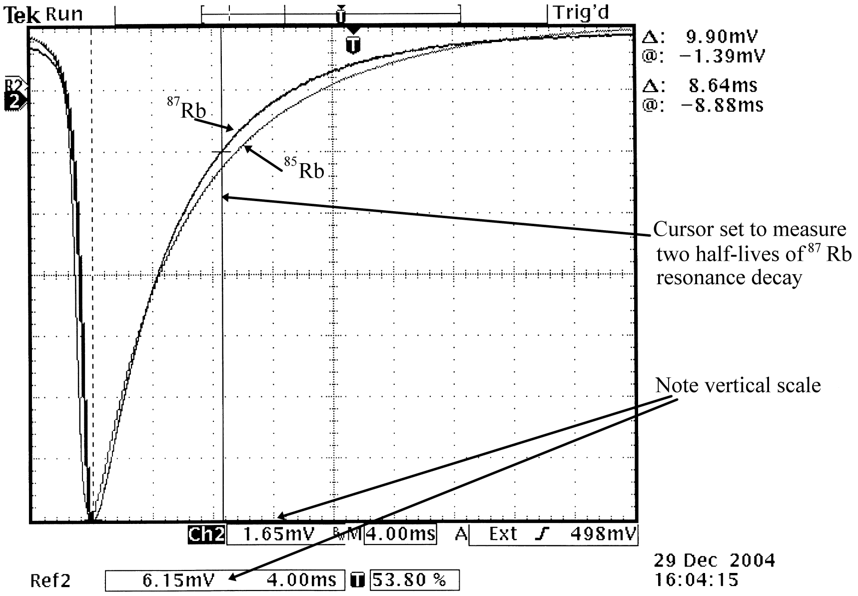
It is interesting to see just how sensitive the signal is to any change in the magnetic field at the location of the Rb cell. A small magnet is available for this test. With a resonance dip like that in Fig. 7 displayed on the scope, bring the magnet close to the aluminum cylinder and observe the effect on the waveform. Then see what happens when you flip the magnet, and bring the opposite end to the cylinder. Can you explain what you see, both in the direction of the shift of the resonance and in how the shape changes?

How would you construct an ideal environment for performing the measurements in this experiment? After you are done, be sure to move the magnet away from the experiment.

4.4 Measuring the relaxation time, τ

In order to better measure the relaxation time after passing through the resonance condition, we will reduce the repetition rate of the B_0 sweep field. This will allow the Rb to come to equilibrium before repeating passage through resonance.

Set the B_0 sweep frequency to 13.0 Hz. Set the B_1 frequency to the resonance for ^{85}Rb, about 220 kHz. Tune the frequency to give the strongest resonant dip—this will occur near the point of zero applied field. Then adjust the offset of the B_0 generator to place the dip a little to the left side of the sweep. You should see the trace relax very closely to the I_∞ level on both sides of the familiar dip. As discussed on page 10 , it is possible to measure τ from this curve by inserting the appropriate values into Eq. (29). Unfortunately, our apparatus does not allow for reducing the light intensity so as to determine τ_{min}. You can, however, measure τ for both isotopes and compare the values. Figure 9 shows the passage through resonance for both isotopes (one curve is stored in Reference 1), and clearly τ is not the same for both.



Cursor set to measure two half-lives of ^{87} Rb resonance decay

Note vertical scale

Figure 9: Resonance dips for both the ^{85}Rb and ^{87}Rb signals superimposed on each other. Note that the vertical scales, as indicated by the “Ch2” and “Ref2” announcers have been set to non-standard values by the fine scale adjust in order to make the signal fill the 8 vertical divisions. The cursors are set to measure the time of $2T_{1/2}$ of one of the resonances, as discussed in the text.

You may measure τ using the digital scope by the following procedure:

1. Maximize the size of the trace so that it takes up a large portion of the scope display. You can make fine adjustments to the vertical scale by means of the “Fine scale” softkey and associated “soft knob” (the same knob is used for changing many parameters, such as the number of averages and cursor positions).
2. Call up the averaging feature and average readings until you get a nice clean trace (i.e., 128 averages).
3. Use the horizontal cursors to determine the difference between I_0 and I_∞.
4. Calculate the value of $(I_0 - I_\infty)/2$ and also $(I_0 - I_\infty)/4$.
5. Then use the “crossed” cursors to measure the time it takes to drop from I_0 to these two values. These numbers should be $T_{1/2}$ and $2T_{1/2}$. Note the cursors in in Fig. 9 are set to measure $2T_{1/2}$ (here equal to 8.64 ms).
6. From these find $T_{1/2}$ and then τ (Recall that $T_{1/2} \neq \tau$; what's the correct relation?)

Record the resonance dip for both isotopes and determine τ for ^{85}Rb and ^{87}Rb. To what do you attribute the difference? (Hint: re-read section 3.1.)

4.5 Studying field inhomogeneities

Set the averaging feature of the digital scope back to average only a few readings (2–4). Adjust the offset of the DS345 back to zero, and retune the B_1 generator to center the resonance dip in the sweep.

Keep all of the other controls at these settings and slowly sweep the frequency of B_1 up and down. Note how the shape of the dip changes as you change the frequency. At what frequency is the dip the sharpest on its left edge? To understand this behavior, recall that in section 3.1, the initial rate of depolarization was argued to depend on the B_0 field's uniformity, as different atoms go through resonance corresponding to different local fields. The total field in the cell is the (vector) sum of all external fields and the field produced by the B_0 solenoid. Do you expect the field from the solenoid to be more or less uniform than the earth's field? Why?

To push this analysis further, study the effect of applying a very non-uniform field: Use the small magnet provided, and approach the aluminum cylinder along a direction perpendicular to the cylinder's axis while watching the resonance on the scope. Note in particular the behavior of the leading edge of the dip as you get closer to the cylinder. Discuss this behavior in your notebook. (You may also want to print some representative scope screens.)

Optimize the resonance in the earth's field again, then make a printout of a resonance dip, and estimate the field inhomogeneity across the Rb cell in terms of parts-per-million per centimeter (ppm/cm). A sample Rb cell from which to obtain dimensions is available in the lab. If there were no inhomogeneities in any of the magnetic fields, to what precision would you be able to measure a magnetic field of about 10 gauss at the location of the cell with the equipment used in this experiment? Would the optical pumping technique be a good way to calibrate an instrument like the gaussmeter? Not surprisingly, some high precision magnetometers are based on the optical pumping technique.

Finally, It is interesting to vary the amplitude of B_1 to see what effect it has on the resonance dip. Is there an optimum amplitude for this signal? What happens when you exceed this amplitude? Discuss your understanding of how the amplitude affects the resonance signal.

4.6 Another method of observing optical pumping

There is another way to observe optical pumping without using the perturbation of the B_1 field. The idea is to redistribute the population of the magnetic sublevels of the ground state when they are in the fully pumped condition. Given the configuration of the experiment, changing anything about the light is not possible. But we do have other ways to control the applied field. Note that when taking measurements to determine g_F, the net magnetic field never changed polarity (how do you justify this claim?). But what if the magnetic field were to reverse polarity? Referring to Eq. (21), if B_0 changes to $-B_0$, the energy changes sign. This implies that atoms in the $m_F = +1$ and $+2$ states are now in the $m_F = -1$ and -2 states, respectively. But this is just the goal we were seeking—to change the population distribution of the magnetic sublevels. After flipping the field from B_0 to $-B_0$, transitions with $\Delta m_F = +1$ are again possible, and pumping action can be observed. Question: are both isotopes participating in the pumping action under these conditions?

Set $B_1 = 0$ by turning off its function generator. Select the square wave waveform on the DS345 function generator, set the amplitude to 0.6 volts, and the frequency to 7 Hz (this is a frequency that will allow for averaging out the 60 Hz noise; to see that this is important, try a frequency of 20 Hz). From your graph of V_{offset} vs. f_{res} which you made during the procedure to determine g_F, determine the offset corresponding to $f_{res} = 0$; this gives the condition necessary to null the earth's field. Set the offset on the DS345 generator to this value. What do you expect to see when the square wave transitions from one level to the other? Change the offset in the positive direction by several volts. What happens to the signal? Change the offset back to the value corresponding to $f_{res} = 0$. Adjust the offset slightly to find the value where the signals on both edges of the square wave are most nearly equal. (Note: you may find that as you move the offset up and down on the DS345 that you hit a point where the generator display shows an error; this means you have reached the limit of the generator output. The DS345 can produce a maximum voltage of ±10 volts into an open circuit, or ±5 volts into 50Ω. You may be able to move the offset to greater values by reducing the amplitude of the square wave, and vice versa.)

Measure the time constant of this signal by using the same scope manipulations as used in section 4.4. How does it compare to the time constants you measured using the B_1 resonance signal?

4.7 Measuring the Earth's field

To calculate g_F from your measurements, you will need to know the earth's field. After you have completed all measurements on the rubidium sample, turn off all the electronics except the gaussmeter. After the electronics are off, consult the TA for help in removing the optical pumping assembly from the aluminum cylinder. Carefully set the assembly aside in a secure place.

Turn on the Bell 9500 gaussmeter and allow it to warm up for a few minutes. Check that the range is on "autorange". It should autorange into the 3 gauss range.

Take the gaussmeter probe and insert it into the small black ZERO GAUSS CHAMBER. Perform the probe zero procedure as follows: find this procedure by pressing the PROGRAM / ENTER button and then using the arrow buttons. Select CHANGE and then press the ENTER button. After the zeroing procedure is complete (takes about 15 seconds), select RUN on the menu and press the ENTER button. Insert the probe into the piece of white foam. Slide this piece of foam into the aluminum housing, and record the reading of the earth's field. Note how the reading is affected by changes in the cylinder's position. The probe is a Hall effect device which is designed to give a maximum amplitude reading when the field is oriented along the probe axis. (Other probes are designed for transverse measurements, e.g., the one used in the NMR experiment.) After recording the field, remove the foam from the housing and remove the probe from the foam. Turn off the gaussmeter.

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