

# A-4 Optical Pumping

## From Physics 191r

Optical Pumping Word version File:A4optpump 10.doc

Optical Pumping PDF version File:A4optpump 10.pdf

## OPTICAL PUMPING

author: Mara Prentiss (2002)

first experiment: II

### Contents

- 1 LEARNING GOALS
- 2 INTRODUCTION
- 3 APPARATUS
  - 3.1 The laser diode
  - 3.2 Optics
  - 3.3 Rb absorption cells
  - 3.4 Photodetector
  - 3.5 Magnetic field
  - 3.6 Helmholtz coil
  - 3.7 Signal generator
  - 3.8 Temperature Control
  - 3.9 Lock-in Amplifier
  - 3.10 Automated data acquisition
    - 3.10.1 Frequency Sweep: LabVIEW
    - 3.10.2 Oscilloscope data transfer: LabVIEW
    - 3.10.3 Oscilloscope data transfer: Matlab
  - 3.11 Spin Exchange
- 4 EXPERIMENTAL PROCEDURE
  - 4.1 Basic
  - 4.2 Optional
- 5 NOTES
- 6 REFERENCES
  - 6.1 Papers
  - 6.2 Monographs
- 7 BENCH NOTES
- 8 LINKS
- 9 APPENDIX: Matlab script for Tektronix data transfer



## LEARNING GOALS

- Understand atomic magnetic moments interacting with magnetic fields in classical and quantum pictures.
- Observe Rabi oscillations.
- Measure relaxation times and g-values for atomic rubidium.
- Perform nonlinear curve fits.

- Practice laser safety.
- Use and understand a lock-in amplifier.
- Observe spin exchange between rubidium and hydrogen, deuterium, nitrogen and free electrons.

## INTRODUCTION

The goal of this experiment is to understand the time evolution of the internal state population distribution in atoms interacting with electromagnetic fields. The experiment uses electromagnetic fields in two different frequency ranges: optical fields with frequencies of  $10^{14}$  Hertz and magnetic fields with frequencies of  $10^6$  Hertz.

The interactions with the magnetic field are the same as those used in NMR and atomic clocks. The interactions are well modeled by the Bloch equations, which describe the quantum mechanical evolution of a particle with magnetic moment  $\mathbf{M}$  in the presence of a magnetic field. The equations are similar to the equations governing the classical time evolution of a particle with magnetic moment  $\mathbf{M}$  in a magnetic field in the presence of damping. Qualitatively, in the absence of damping, one would expect that if the magnetic moment is not initially aligned with the magnetic field, the magnetic moment precesses around the magnetic field direction at the Larmor frequency, maintaining a constant angle between the direction of the magnetic field  $\mathbf{B}$  and the direction of the magnetic moment,  $\mathbf{M}$ . The effect of damping will be to cause the motion to decay toward some equilibrium value. Quantum mechanically the damping process is the result of collisions with other atoms. Classically, as quantum mechanically, it is convenient to solve the problem in the rotating reference frame where the precessing magnetic moment is not rotating. Notice, that if the system is initially at equilibrium, there will be no time evolution at all. The projection of the magnetic moment along the magnetic field direction can be measured using various techniques. In this experiment, the projection is measured by monitoring the light that is absorbed from a laser beam that passes through the sample.

The laser light is not only used to monitor the population in the sample, optical pumping due to the light is also used to transfer the magnetic moment out of thermal equilibrium. It is important to note that the time scales for the two processes are very different. One can assume that the ground/excited electronic transition is at equilibrium, so the absorption signal measures the instantaneous population distribution in the ground state, even though distribution of population among  $m_F$  sublevels of the ground state is not in equilibrium.

Optical pumping is a process in which light is absorbed by an atom in a ground state resulting in a transfer of the atom from a ground electronic state to an excited electronic state. Spontaneous emission then transfers the atom from the excited electronic state, back to the ground state. If the polarization of the spontaneously emitted light is different than the polarization of the absorbed photon, then the final ground state of the atom will have a different  $m_F$  value from the initial state. In the simplest case, where the static magnetic field is aligned along the propagation vector of the light, sigma plus polarized light will transfer all of the atoms into the magnetic sublevel with the highest  $m_F$  value, whereas in the equilibrium distribution the atoms are evenly distributed between the sublevels. In the case where the intensity of the optical pumping light is weak, the characteristic time for the optical pumping process is the characteristic time between optical absorptions, a time that can be much longer than the 100 ns lifetime of the excited state. It is useful to conduct experiments with different optical pumping times.

It is important to understand the relationship between the magnetic moment  $\mathbf{M}$  and  $m_F$  level of the atom, since the optical pumping transfers atoms between magnetic sublevels, but the magnetic field equations are written in terms of the magnetic moment  $\mathbf{M}$ .<sup>[1]</sup> The final equilibrium state will balance the decay of the magnetic moment due to interactions between the atoms and their environment, with the optical pumping that preferentially transfers atoms into internal states with higher  $m_F$  values.

## APPARATUS

A laser diode is used as the light source. The absorption cell is centered in a large solenoid and is shielded from ambient magnetic fields by a cylindrical mu-metal enclosure. A modulated RF signal is applied to a pair of Helmholtz coils, which surround the absorption cell and are oriented perpendicular to the solenoid axis. A lens focuses light transmitted through the absorption cell onto a photodetector whose output is monitored on an oscilloscope and/or lock-in amplifier. Following are some important details:

### The laser diode

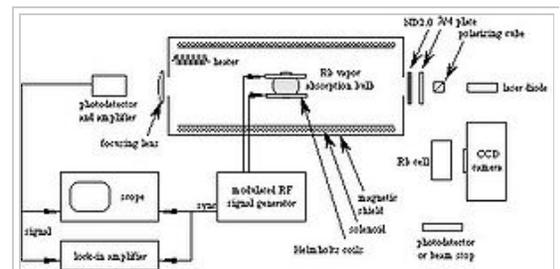


Figure 1. Optical pumping schematic

The laser system is a tunable laser diode with grating feedback.<sup>[2]</sup> The first-order beam from a diffraction grating (Figure 2-pointer 1) defines an external cavity. The temperature of the laser is stabilized and a feedback circuit may be used to lock the laser frequency to the absorption profile of rubidium.

The free-running wavelength of the laser<sup>[3]</sup> is 790 nm. In order to reach the rubidium D1 line (794.98 nm (vac)), the laser is operated above room temperature. The temperature control is accomplished in two stages. The coarse stage utilizes two thermoelectric coolers ([http://en.wikipedia.org/wiki/Thermoelectric\\_cooling](http://en.wikipedia.org/wiki/Thermoelectric_cooling)) (TECs) between a baseplate (Figure 2-pointer 2) on which the laser collimating tube and lens (Figure 2-3) are mounted, and the aluminum box (Figure 2-4) which houses the laser. In general temperature control requires heating and cooling to reach a stable set point. In this case, the TEC pumps heat from the aluminum block under the laser housing into the baseplate directly under the laser package. Cooling is by heat loss to the ambient environment. The magnitude and polarity of the TEC current is chosen so that the laser temperature stabilizes just below the desired setpoint.

Fine temperature control is provided by a circuit with feedback. The feedback element is a thermistor (<http://en.wikipedia.org/wiki/Thermistor>) (Figure 2-5) mounted near the laser. This circuit powers an orange heater tape (Figure 2-6) and compares the thermistor resistance to a fixed setpoint resistance. An analog meter on the front panel of the temperature controller measures the voltage applied to the heater. Choose the TEC current so that the meter reads on-scale (0.2 - 0.6 mA). This choice will depend on the ambient temperature in lab. A typical TEC current is 1.3 A (dial 6.6). The TEC requires an external power supply.<sup>[4]</sup> Always change the TEC current slowly (i.e. reduce the current to zero before switching off the power supply). Good temperature stability will be achieved a few hours after the temperature controller and TEC current are turned on. The wavelength of the laser will be near the rubidium D1 line when the "THERMISTOR" output (Figure 3-7) (and "SETPOINT" control (Figure 3-8)) of the temperature controller are near 5.17 Volts. This voltage corresponds to approximately 50°C. One can measure laser properties at other temperatures, but this is not recommended. The I to V converters (Figure 3-9) are no longer used.

The laser current also affects the wavelength; it is used as a fine control to match the rubidium D1 line. Typical laser current is around 100 mA. The absolute maximum current for the laser is 120 mA. Use the potentiometer (Figure 4-10) to ramp up the current slowly from zero to the desired operating current. The laser may be left on for the duration of the lab session but turned off overnight. This prolongs the life of the laser. **Always change the laser current slowly (i.e. reduce the current to zero before turning off the power supply).** The current supply<sup>[5]</sup> has a monitor output (Figure 4-11) (10 mV/mA), which is referenced to negative six volts. BECAUSE THE SHELL OF THE BNC MONITOR OUTPUT IS FLOATING, IT IS ISOLATED FROM THE CHASSIS GROUND. IT SHOULD NEVER BE ATTACHED TO A GROUNDED INSTRUMENT SUCH AS AN OSCILLOSCOPE. Instead use one of the Fluke multimeters which have floating inputs. The laser power supply also has a program input (Figure 4-12) (24 mA/V). The current set by the front panel dial (Figure 4-10) is added to that called for by the program input. Use slow modulation only (NO SAWTOOTH!).

If necessary, the laser may be locked to the rubidium D1 line using a PZT and feedback circuit. Consult the faculty or staff if the unlocked laser is not stable enough.

**SAFETY WARNING: THE NOMINAL MAXIMUM POWER OF THE SHARP LT025MD IS 40 mW. THE DIRECT BEAM OR SPECULAR REFLECTION OF THE DIRECT BEAM CAN PERMANENTLY DAMAGE YOUR VISION. USE EXTREME CAUTION WHEN ALIGNING THE LASER. BE CERTAIN THAT ALL BEAMS ARE CONTAINED WITHIN THE FOOTPRINT OF THE LAB BENCH. LASER SAFETY GOGGLES ARE AVAILABLE. USE THEM DURING OPTICAL ALIGNMENT AND WHENEVER ANYTHING IS INSERTED INTO OR REMOVED FROM THE BEAM PATH.**

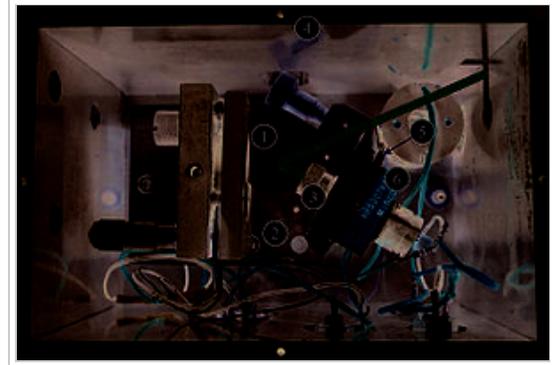


Figure 2. Optical pumping laser



Figure 3. Optical pumping laser temperature control



Figure 4. Optical pumping laser current supply

## Optics

The beam leaving the aluminum laser housing is collimated and linearly polarized. The first optic in the beam path is a polarizing cube. A (redundant) linear polarizer and a quarter-wave plate have been cemented onto the upstream face of the polarizing cube. The resulting circularly polarized light is split 50/50 by the polarizing cube. The beam which goes off at 90° to the original direction (the "locking beam") is used to locate the rubidium resonance by observing fluorescence in a rubidium vapor cell. This beam hits a photodetector or a beamstop downstream of the locking cell.

The beam, which continues parallel to the original direction, is used for the optical pumping. The height of this beam is increased to coincide with the axis of the solenoid by two mirrors. It then passes through another quarter wave plate, the orientation of which is variable.

A beam expander may be constructed using two lenses before the beam enters the solenoid. This is not necessary to observe optical pumping. It may be desirable to expand the beam when looking for the spin exchange signal.

The last optic upstream of the pumping cell is a neutral density filter. On the order of one hundred times more light than needed is generated by the laser.

Downstream of the pumping cell, a lens focuses the beam onto the photodetector.

## Rb absorption cells

The pumping cells are spherical glass bulbs, which contain Rb metal, a buffer gas, and in most cases, an exchange gas. The buffer gas reduces the mean free path of the rubidium atoms, minimizing collisions with the wall of the cell. This is necessary to preserve the polarization of the rubidium. *The cells are fragile and difficult to replace. Use extreme caution while handling the cells.*

A cylindrical cell, which contains only Rb metal, is also available. This cell is used to observe fluorescence of the rubidium and/or to lock the laser. The locking beam passes through the cylindrical cell and hits a beam stop. A CCD camera and monitor are used to observe the fluorescence of the rubidium atoms. When the laser is tuned to the rubidium resonance, the beam becomes visible on the monitor. The laser current is used as a fine control of the optical frequency to tune on to resonance. The hyperfine structure of the two rubidium isotopes is visible in this cell but not in the pumping cells. The following table identifies the contents of the bulbs:

### ABSORPTION CELLS

- all pressures are expressed in cm of oil at 25°C
- the density of the oil was 0.906g / cm<sup>3</sup>

Bulb ID no.	volume(cm <sup>3</sup> )	isotope	buffer gas
400	200	Rb87	43.6 cm He
2	500	Rb + 0.84 cm H2	91.61 cm Ne
14	500	Rb + 0.74 cm H2	37.02 cm Ne
15	500	Rb + 0.63 cm H2	45.06 cm Ne
28	500	Rb + 1.03 cm D2	29.87 cm Ne
31	500	Rb + 0.93 cm D2	76.57 cm Ne
40	500	Rb + 0.85 cm D2	46.10 cm Ar
67	300	Rb + 1.12 cm H2	64.32 cm Ne
71	300	Rb + 0.75 cm H2	13.90 cm Ar
95	300	Rb + 1.59 cm N15	43.18 cm He
96	300	Rb + 1.43 cm N15	62.21 cm He
100	300	Rb + 1.10 cm N15	95.03 cm He
101	300	Rb + 1.50 cm N14	16.56 cm He
102	300	Rb + 1.43 cm N14	34.99 cm He

## Photodetector

We wish to observe the transmitted light, which is modulated by the time-varying absorption of the rubidium cell. Our interest is not in the DC intensity, but only in the modulation. Detection is accomplished with a silicon photodiode with integral amplifier.<sup>[6]</sup> An 800 nm interference filter<sup>[7]</sup> positioned in front of the detector makes it possible to operate with the room lights on.

Time-averaging the photodetector output is possible with the Tektronix TDS 3012 oscilloscope. This technique can greatly increase the signal-to-noise ratio.

## Magnetic field

The rubidium cell is shielded from the earth's magnetic field by a large mu-metal<sup>[8]</sup> cylinder with mu-metal endcaps. Inside the shield, wound on a 12" diameter split aluminum cylinder, is a 27.75" long solenoid consisting of  $1064 \pm 4$  turns of #16 enameled wire. A 9 V pack of 6-C cell batteries provides the solenoid current. A 10-turn potentiometer allows fine adjustment of the current from 5 to 50 milliamps. The voltage across a 1  $\Omega$  series resistor is used to monitor the current through the solenoid. The magnetic field can be calculated from the current and solenoid properties.

## Helmholtz coil

The magnetic field produced by the Helmholtz coil is 0.69 Gauss/Amp.

## Signal generator

The time-domain optical pumping signal is observed by driving the atoms out of the pumped state through a Zeeman transition. The Zeeman splitting is created by a dc magnetic field as described above. The Zeeman transition is driven by an rf magnetic field which is generated by applying an rf voltage across Helmholtz coils. If the rf magnetic field were on continuously, both pumping and depumping would be continuous and the system would reach a steady state. Therefore a chopped rf signal is used. Begin with a continuous sine wave, then add square wave amplitude modulation. The scope can be triggered or the lock-in referenced to a modulation output on the rear panel of the SRS generator.<sup>[9]</sup> Typical modulation rep rates are 10-100 Hz. Start with about 23 Hz. The carrier wave frequency will depend on the magnetic field strength and is typically in the tens or hundreds of kHz range.

It is also possible to observe the effect in the frequency domain with a frequency-modulated rf signal. More on this below under "LabVIEW vi".

## Temperature Control

If desired, the cell can be heated to increase the vapor pressure of the rubidium. The optical pumping signal can be observed with the pumping cell at room temperature, but spin exchange requires heating the cell.

The heater is located outside of the chamber housing the rubidium bulb and Helmholtz coils. A dc power supply<sup>[10]</sup> energizes the heater. Operating the heater at 20V (3A) for about one hour brings the temperature to 40 °C, a typical temperature. The heater can then be turned off. (Use the dials – don't just switch off the power supply!) The time constant for cooling is greater than 3 hours. Do not exceed 25V or 50 °C. If continuous operation of the heater is desired, set the voltage at 13V. This will give a steady-state temperature of 44 °C. The temperature inside the solenoid is monitored with a Hewlett Packard platinum film thermometer.<sup>[11]</sup> The temperature probe is slightly magnetic. Remove it from the chamber before making final measurements.

## Lock-in Amplifier

For rubidium, the Rabi oscillations can be observed on an oscilloscope. Detuning either the frequency of the rf magnetic field or the amplitude of the dc magnetic field from resonance causes a decrease in the amplitude of the signal. In order to measure the linewidth of the resonance quantitatively, a single number must be generated to characterize the amplitude of the signal, which is fairly complicated. The lock-in amplifier generates such an average voltage.

The lock-in<sup>[12]</sup> is a phase sensitive detector. It multiplies the input by a reference to downshift the ac signal to a dc signal proportional to the input, for the result. Whatever component of the input has the same frequency and phase as the reference gives a nonzero signal

if the RC filter time (which determines the time constant) is at least one period of the modulation. The amplified signal is available at the output on the lock-in's front panel. Analog and digital meters on the front panel also indicate the magnitude of the output voltage.

The real strength of the lock-in is that it can detect signals, which are orders of magnitude smaller than the noise present at its input. The spin exchange signals are too weak to observe with the oscilloscope, but they can be detected using the lock-in.

## Automated data acquisition

### Frequency Sweep: LabVIEW

A LabVIEW virtual instrument called "Scan FM Drive.vi" enables one to measure the linewidths of the optical pumping resonances. See the figure below. The vi steps the frequency of one of the SRS synthesizers while measuring voltages from both Fluke multimeters<sup>[13]</sup> over a GPIB bus. One of the Flukes should measure the analog output from the lock-in. The vi graphs the result and saves the measurement to disk. The time between frequency steps (Dwell) must be several lock-in time constants since the modulation output, which is used for lock-in reference, turns off during each step.

- (Figure 5-1). Controls #1 set parameters of the DS345 function generator. The control labeled DS345 having a value of 1 in the figure is the GPIB address of the DS345. Press SHIFT  $\pm$ , twice, on the DS345 front panel to verify the address. The indicators to the right of the controls give the current values of the respective parameters.
- (Figure 5-2). Controls #2 are the GPIB addresses of the two Fluke multimeters. Press the LOCAL key on the meters to verify the addresses.
- (Figure 5-3). Controls #3 are used to save data. Set the Save switch to YES before running the vi. Frequency Sweep mode of Automatic means that the vi steps the frequency of the DS345 output. Manual means that an external sweep is used.
- (Figure 5-4), (Figure 5-5), and (Figure 5-6) are indicators showing graphs of  $V_1$  and  $V_2$  vs. frequency and  $V_1$  vs.  $V_2$  respectively.

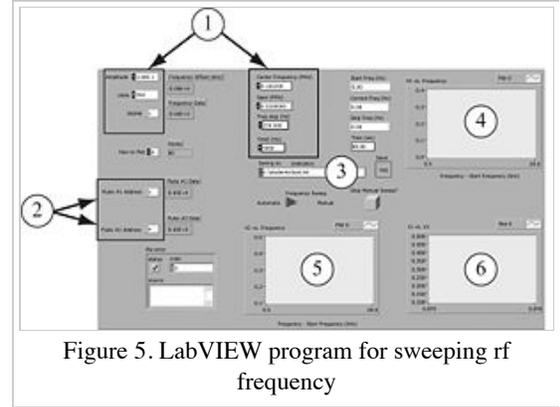


Figure 5. LabVIEW program for sweeping rf frequency

If desired, frequency modulation can be used instead of amplitude modulation. In this case, the lock-in will be detecting the change in signal amplitude. The SRS synthesizers can be set up either to step or sweep the center frequency of the modulated signal. Two rf signals must be mixed and filtered to create the continuous sweep. The LabVIEW vi has a "Manual Sweep" option which is used in this case.

### Oscilloscope data transfer: LabVIEW

Data transfer from the Tektronix TDS3012 oscilloscope is also available over the GPIB bus. The LabVIEW program, "OP\_Tek\_reader" has only two controls, "channel to read" and "save full data file?". Set the controls appropriately and click the run arrow. The LabVIEW graph indicator should look the same as your scope channel. OP\_Tek\_reader assumes that the GPIB address of the scope is 5, the default value. If needed, it can be changed under the Utility:System I/O:GPIB menu.

### Oscilloscope data transfer: Matlab

Matlab enthusiasts can transfer time-domain data from the Tektronix TDS3012 oscilloscope over the GPIB bus. The scope's GPIB address is 5. A Matlab object, TekGPIBobj contains this and other information about how to talk to the scope. A script, TekTransfer.m for transferring channels 1 and 2 is available in C:\students, and in an appendix below. The data is transferred in binary and converted to floating point arrays, ch1v and ch2v which appear in the workspace when the script runs successfully. Read the comments in the script before running it. To run the script at the command line, type >>TekTransfer()

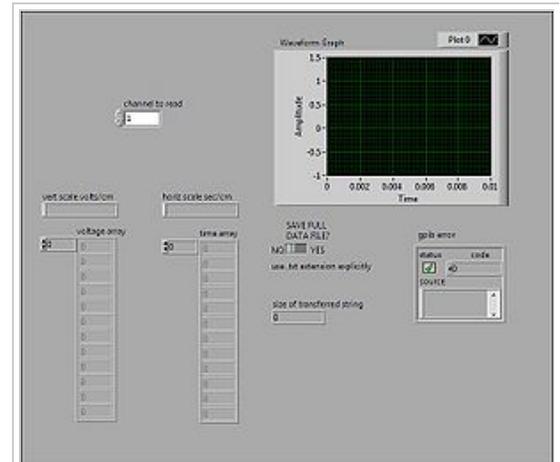


Figure 6. LabVIEW program for oscilloscope data transfer

## Spin Exchange

Those bulbs containing exchange gases such as nitrogen or hydrogen are equipped with electrodes so one can use a discharge to dissociate the hydrogen and nitrogen molecules. The nitrogen system is a lot of fun because the hyperfine splitting is very small and one can observe the hyperfine transitions. When investigating spin exchange collisions, it is important to optimize the rubidium signal and to minimize the disturbing effects of the discharge. The discharge can be produced using either a high-voltage transformer<sup>[14]</sup> or a short-wave transmitter.<sup>[15]</sup> In either case, a rule-of-thumb is to apply only enough power to just barely see the discharge. Ask one of the faculty or staff to help you set this up safely.

Care must be taken to align the optics in such a way that the laser beam passes through a region of the cell where the glow discharge is visible.

The following is some relevant data concerning the ground state of the isotopes:

atom	spin	hyperfine splitting(MHz)
Rb85	5/2	3037.730
Rb87	3/2	6834.681
H	1/2	1420.405761
D	1	327.384
N14	1	26.12721
N14	1	15.67646
N15	1/2	29.29136

## EXPERIMENTAL PROCEDURE

Open up the apparatus to see which absorption bulb is in place. Familiarize yourself with the instrumentation. Adjust the optical alignment. You will have to use the IR-sensitive card to "see" the beam. The focusing lens is set so that all the light falls on the photocell. Here are some suggestions for measurements you can undertake:

### Basic

- Study the transient phenomenon when the RF field is turned off and on.
- Measure precisely the ratio of the g factors of the electron magnetic moments for  $^{87}\text{Rb}$  and  $^{85}\text{Rb}$ .
- Determine the nuclear spin of  $^{87}\text{Rb}$  and  $^{85}\text{Rb}$ .
- Study the line width as a function of RF field and light intensity.
- Determine the  $T_1$  and  $T_2$  relaxation times and the pumping time.

### Optional

- Measure inhomogeneous broadening due to  $B_0$  gradients.
- Observe diffusion through  $B_0$  gradients.
- Study diffusion through the light beam as a function of buffer gas properties.
- Measure the spin exchange relaxation rate for  $^{85}\text{Rb} \Rightarrow ^{87}\text{Rb}$ .
- Compare the lineshapes of rubidium resonance in paraffin-coated cells to buffer gas cells (under development).
- Measure the frequency of the Rabi oscillations as a function of rf field amplitude.
- Measure the g factor of the free electron through spin exchange collisions.
- Measure the g factor and spin of atomic hydrogen.
- Measure the g factor and spin of  $^{14}\text{N}$  and  $^{15}\text{N}$ .

## NOTES

1. ↑ See [Appendix 12  
([https://coursewikis.fas.harvard.edu/phys191r/Evolution\\_of\\_a\\_Magnetic\\_Moment\\_in\\_Static\\_and\\_Oscillating\\_Magnetic\\_Fields](https://coursewikis.fas.harvard.edu/phys191r/Evolution_of_a_Magnetic_Moment_in_Static_and_Oscillating_Magnetic_Fields))  
] for a discussion of the behavior of magnetic moments in static and rotating fields.
2. ↑ The design of the laser is based on a paper by C. Weimann: Am. J. Phys 60, 1098 (1992).

3. ↑ Sharp LT025MD
4. ↑ Lambda LH 125FM
5. ↑ Thorlabs LD1250
6. ↑ Thorlabs PDA36A
7. ↑ Thorlabs FB 800-40
8. ↑ Mu-metal is a high-permeability iron alloy (sometimes called permalloy) and is commonly used to shield cathode ray and photomultiplier tubes. The cylinder is 14" in dia. x 30" long.
9. ↑ Stanford Research Systems. Model DS345. 30 MHz Synthesized Function Generator.
10. ↑ Kepco KS-60-20M
11. ↑ HP 2802A Thermometer.
12. ↑ Stanford Research Systems SR510.
13. ↑ Fluke 8840A.
14. ↑ 7,500 VAC "neon sign" transformer; the output is controlled with a variac on the primary.
15. ↑ Viking Challenger 6 to 80 meter band transmitter

## REFERENCES

### Papers

- L.W. Anderson, F.M. Pipkin and J.C. Baird, Jr., Phys Rev 120, 1279 (1960). Hyperfine Structure of Hydrogen, Deuterium, and Tritium (<http://www.fas.harvard.edu/~phys191r/References/a4/Anderson.pdf>)
- D. Budker, D.J. Orlando, V. Yashchuk, Am J Phys 67, 584 (1999). Nonlinear Laser Spectroscopy and Magneto-optics (<http://www.fas.harvard.edu/~phys191r/References/a4/Budker.pdf>) . Deals primarily with Faraday rotation, but also useful for optical pumping.
- R. Benumof, Am J Phys 33, 151 (1965). Optical Pumping Theory and Experiments (<http://www.fas.harvard.edu/~phys191r/References/a4/Benumof.pdf>)
- A.L. Bloom, Scientific American 203, 72, (Oct. 1960). Optical Pumping (<http://www.fas.harvard.edu/~phys191r/References/a4/Bloom.pdf>)
- H.G. Dehmelt, Phys Rev 105, 1487 (1957). Slow Spin Relaxation of Optically Pumped Sodium Atoms
- H.G. Dehmelt, Phys Rev 105, 1924 (1957). Modulation of a Light Beam by Precessing Absorbing Atoms
- H.G. Dehmelt, Phys Rev 109, 381 (1958). Spin Resonance of Free Electrons Polarized by Exchange Collisions. Discusses techniques for measuring T1 and T2.
- R.L. DeZafra, Am J Phys 28, 646 (1960). Optical Pumping (<http://www.fas.harvard.edu/~phys191r/References/a4/deZafra.pdf>)
- A.H. Firester, Am J Phys 36, 366 (1968). Inexpensive Rubidium - D2 Filter (<http://www.fas.harvard.edu/~phys191r/References/a4/Firester.pdf>)
- W. Franzen, Phys Rev 115, 850 (1959). Spin Relaxation of Optically Aligned Rubidium Vapor (<http://www.fas.harvard.edu/~phys191r/References/a4/Franzen.pdf>)
- W. Happer, Rev Mod Phys 44, 169 (1972). Optical Pumping (<http://www.fas.harvard.edu/~phys191r/References/a4/Happer.pdf>) This article is difficult, and contains a complete set of references.
- W.B. Hawkins, Phys Rev 98, 478 (1955). Orientation and Alignment of Sodium by Means of Polarized Resonance Radiation (<http://www.fas.harvard.edu/~phys191r/References/a4/Hawkins.pdf>)
- G.S. Hayne, E.S. Ensberg, and H.G. Robinson, Phys Rev 171, 20, (1968). Measurements of g Ratios for Rb85, Rb87, Hydrogen, and Deuterium, and of the Hyperfine Separation of Deuterium (<http://www.fas.harvard.edu/~phys191r/References/a4/Hayne.pdf>)
- W.M. Hughes, H.G. Robinson, Phys. Rev. Lett. 23, 1209, (1969). Determination of Isotope Shift in the Ratio of Atomic gJ Values of Hydrogen and Deuterium. An atomic beam experiment.

S.G. Kukulich, Am J Phys 36, 420 (1968). Time Dependence of Quantum State Amplitudes: Demonstrated by Free Precession of Spins (<http://www.fas.harvard.edu/~phys191r/References/a4/Kukulich.pdf>)

K. B. MacAdam, A. Steinbach and C. Wieman, "A narrow-band tunable diode laser system with grating feedback..." (<http://www.fas.harvard.edu/~phys191r/References/a4/MacAdam.pdf>) " Am. J. Phys. 60, 1098 (1992). A nuts and bolts article. A good introduction to laser diode systems.

H.W. Moos, Am J Phys 32, 589 (1964). Resource Letter MOP-1 on Masers and Optical Pumping (<http://www.fas.harvard.edu/~phys191r/References/a4/Moos.pdf>)

M. Nagel and F.E. Haworth, Am J Phys 34, 553 (1966). Advanced Laboratory Experiments on Optical Pumping of Rubidium Atoms - Part I: Magnetic Resonance (<http://www.fas.harvard.edu/~phys191r/References/a4/Nagel.pdf>)

D.A. Steck. Rubidium 87 D Line Data (<http://www.fas.harvard.edu/~phys191r/References/a4/rb87.pdf>) .

C.W. White, W.M. Hughes, G.S. Hayne, H.G. Robinson, Phys. Rev. 174, 23 (1968). Determination of g-Factor Ratios for Free <sup>85</sup>Rb and <sup>87</sup>Rb Atoms. An apparatus very similar to ours was used for this experiment. Many helpful details are presented.

## Monographs

R. Bernheim, Optical Pumping: an introduction (<http://www.fas.harvard.edu/~phys191r/References/a4/Bernheim.pdf>) , (W.A. Benjamin, NY, 1965). Cabot QC357.B47

E.U. Condon and G.H. Shortley, The Theory of Atomic Spectra (<http://www.fas.harvard.edu/~phys191r/References/a4/Condon.pdf>) , (Cambridge University Press, Cambridge, 1970).

G. Herzberg, Atomic Spectra & Atomic Structure (<http://www.fas.harvard.edu/~phys191r/References/a4/Herzberg.pdf>) , (Dover, NY, 1944).

J. J. Sakurai, Modern Quantum Mechanics (<http://www.fas.harvard.edu/~phys191r/References/a4/Sakurai.pdf>) , (Addison-Wesley Publishing Company, NY, 1985). pp 320-25.

Vanier, J. and Audoin, C., The Quantum Physics of Atomic Frequency Standards, (Bristol, Philadelphia, 1989).

## BENCH NOTES

- Appendix 12: Magnetic Precession in Static and Oscillating Magnetic Fields (<http://www.fas.harvard.edu/~phys191r/pdf/ap12.pdf>)
- Sharp LT025MD Laser Diode ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/A4/SharpLaser.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/A4/SharpLaser.pdf))
- Stanford Research DS345 RF Generator ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/A4/RFgenerator.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/A4/RFgenerator.pdf))
- SR510 Lock-in Amplifier ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/SR510.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/SR510.pdf))
- Circuit Diagrams ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/A4/CircuitDiagrams.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/A4/CircuitDiagrams.pdf))
- Laser Characterization ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/A4/LaserCharacterization.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/A4/LaserCharacterization.pdf))
- Burleigh WA2500 Wavemeter ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/A4/BurleighWavemeter.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/A4/BurleighWavemeter.pdf))
- Thorlabs LD1250 Laser Current Source ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/A4/Lasercurrentsource.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/A4/Lasercurrentsource.pdf))
- Thorlabs PDA36a Photodetector ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/A4/pda36a.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/A4/pda36a.pdf))
- Calculated fluorescence spectrum from natural abundance rubidium (David Phillips) ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/A4/rb\\_dphilips.jpg](http://www.fas.harvard.edu/~phys191r/Bench_Notes/A4/rb_dphilips.jpg))
- Notes on rubidium vapor density, mean free path, etc. (David Phillips) ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/A4/masernotes.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/A4/masernotes.pdf))
- Dell Optiplex 980 Technical Guide ([http://www.fas.harvard.edu/~phys191r/Bench\\_Notes/optiplex-980-tech-guide.pdf](http://www.fas.harvard.edu/~phys191r/Bench_Notes/optiplex-980-tech-guide.pdf))

## LINKS

- Rubidium energy level diagrams and vapor pressure as a function of temperature (David Phillips) (<http://cfa-www.harvard.edu/~dphil/work/rbmaser/index.html>)

## APPENDIX: Matlab script for Tektronix data transfer

```

% This script transfers channel 1 and channel 2 waveforms from
% a Tektronix 30XX oscilloscope to Matlab.
% >>instrhwinfo('gpib') should return
% ans =
% InstalledAdaptors: {'advantech' 'contec' 'ni'}
% JarFileVersion: 'Version 2.10.0'
% Use >>tmtool if this is not the case.
% BEFORE RUNNING THIS SCRIPT:
% The GPIB interface information is contained in the
% Matlab object, TekGPIBobj in the saved workspace.
% Open scope_gpib_workspace.mat which is located in C:\students
% >>load('scope_gpib_workspace.mat')
% Set the buffer size large enough to hold one waveform
% >>TekGPIBobj.InputBufferSize=100000
% Open a connection to the scope
% >>fopen(TekGPIBobj)
% Set the data transfer format to binary:
fprintf(TekGPIBobj,'data:encdg ribinary');
% query scope for timebase.
% returned value is time per division.
fprintf(TekGPIBobj,'horizontal:scale?');
tpd=fscanf(TekGPIBobj);
% convert character into number in exponential format.
TimePerDiv=sscanf(tpd,'%e')
% calculate time per data point.
% the scope has ten horizontal divisions
% and 10000 data points.
tpp=10*TimePerDiv/10000;
% make an array of time points.
% ignore "negativeness" of times before the trigger event.
time=[tpp:tpp:1e+4*tpp];

```

```

% query scope for vertical position of channel 1.
fprintf(TekGPIBobj,'ch1:position?');
pos1=fscanf(TekGPIBobj);
Position1=sscanf(pos1,'%e')

% query scope for vertical position of channel 2.
fprintf(TekGPIBobj,'ch2:position?');
pos2=fscanf(TekGPIBobj);
Position2=sscanf(pos2,'%e')

% query scope for vertical scale of channel 1.
fprintf(TekGPIBobj,'ch1:scale?');
vpd1=fscanf(TekGPIBobj);
VoltsPerDiv1=sscanf(vpd1,'%e')

% query scope for vertical scale of channel 2.
fprintf(TekGPIBobj,'ch2:scale?');
vpd2=fscanf(TekGPIBobj);
VoltsPerDiv2=sscanf(vpd2,'%e')

% query scope for waveform 1.
fprintf(TekGPIBobj,'data:source ch1');
fprintf(TekGPIBobj,'curve?');
ch1b=fread(TekGPIBobj,10000,'int16');

% query scope for waveform 2.
fprintf(TekGPIBobj,'data:source ch2')
fprintf(TekGPIBobj,'curve?');
ch2b=fread(TekGPIBobj,10000,'int16');

% convert bytes into voltages.
% 2^16 bytes correspond to ten vertical divisions.
% (even though the scope only displays eight)
% center of the screen is zero, positive 2^15 - 1 above
% and negative 2^15 below.

ch1v=VoltsPerDiv1*((ch1b/6553.6) - Position1);
ch2v=VoltsPerDiv2*((ch2b/6553.6) - Position2);

```

```
% plot voltage as a function of time.
```

```
plot(time,ch1v)
```

```
figure;plot(time,ch2v)
```

```
% Before shutting down Matlab, close the connection to the scope:
```

```
% >>fclose(TekGPIBobj);
```

```
Retrieved from "https://coursewikis.fas.harvard.edu/phys191r/A-4\_Optical\_Pumping"
```

---

- This page was last modified on 9 October 2012, at 16:55.

