OPTICAL PUMPING

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 **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 **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 B and the direction of the magnetic moment, 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.

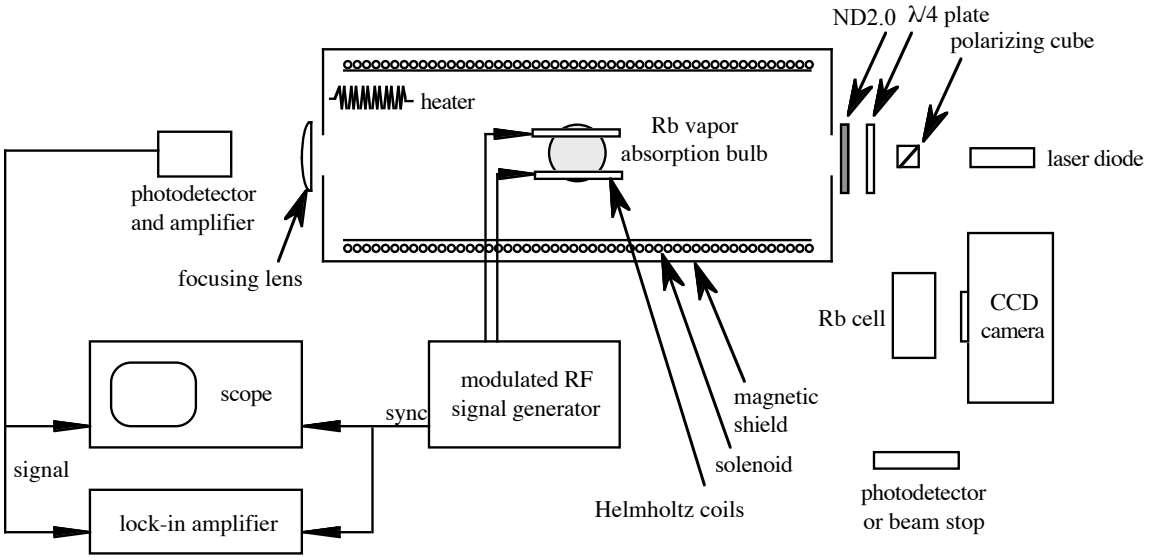
It is important to understand the relationship between the magnetic moment **M** and m_F level of the atom, since the optical pumping transfers atoms between magnetic sublevels, but the magnetic field equations are written in terms of the magnetic moment **M**.* The final equilibrium state will balance 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

* See Appendix 12 for a discussion of the behavior of magnetic moments in static and rotating fields.

monitored on an oscilloscope and/or lock-in amplifier. Following are some important details:



The laser diode

Our laser system is a tunable laser diode with grating feedback.[1] The first-order beam from a diffraction grating 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. See the appendix for a short discussion of principles of operation of the laser.

The free-running wavelength of our laser[2] is 790 nm. In order to reach the rubidium D_1 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 (TECs) between a baseplate on which the laser is mounted and the aluminum box which houses the laser. The polarity of the TEC current is such that the housing is cooled and the laser is heated. The fine temperature control is handled by a temperature control circuit, which compares the resistance of a thermistor mounted near the laser to a setpoint resistance. This circuit powers a heater mounted near the laser. 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 (Lambda LH 125FM) Always change the TEC current slowly (i.e. reduce the current to zero before turning off the power supply). Good temperature stability will be achieved a few hours after the

[1]The design of the system is based on a paper by C. Weimann: Am. J. Phys **60**, 1098 (1992).
[2]Sharp LT025MD

temperature controller and TEC current are turned on. The wavelength of the laser will be near the rubidium D_1 line when the "THERMISTOR" output (and "SETPOINT" control) of the temperature controller is about 5.17 Volts. This voltage corresponds to about 50˚C.

The laser current also affects the wavelength; it is used as a fine control to match the rubidium absorption. The diode should be operated around 100 mA. The absolute maximum current for the laser is 120 mA. **THE CURRENT SOURCE SHOULD NEVER BE TURNED ON OR OFF WHILE CONNECTED TO THE LASER. CURRENT SPIKES RESULTING FROM TURN-ON OR TURN-OFF MAY DESTROY THE LASER.** Instead the supply should be turned on, current control set to zero, then plugged into the laser housing. The current is then ramped up slowly from zero to the desired operating current. The supply may be left on for the duration of the experiment, **BUT THE LASER CURRENT SHOULD BE TURNED TO ZERO WHILE THE LASER IS NOT BEING USED.** This prolongs the life of the laser. The current supply[3] has a monitior output (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**. The laser power supply also has a program input (24 mA/V). The current set by the front panel dial 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 D_1 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 PLACED IN THE BEAM PATH.

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

[3] Thorlabs LD1250

used 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 0.906 gm/cm^3

Bulb Identification no.	volume (cm^3)	isotope	buffer gas
400	200	Rb^{87}	43.6 cm He
2	500	Rb + 0.84 cm H_2	91.61 cm Ne
14	500	Rb + 0.74 cm H_2	37.02 cm Ne
15	500	Rb + 0.63 cm H_2	45.06 cm Ne
28	500	Rb + 1.03 cm D_2	29.87 cm Ne
31	500	Rb + 0.93 cm D_2	76.57 cm Ne
40	500	Rb + 0.85 cm D_2	46.10 cm Ar
67	300	Rb + 1.12 cm H_2	64.32 cm Ne
71	300	Rb + 0.75 cm H_2	13.90 cm Ar
95	300	Rb + 1.59 cm N_{15}	43.18 cm He
96	300	Rb + 1.43 cm N_{15}	62.21 cm He
100	300	Rb + 1.10 cm N_{15}	95.03 cm He
101	300	Rb + 1.50 cm N_{14}	16.56 cm He
102	300	Rb + 1.43 cm N_{14}	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.[4] An 800 nm interference filter[5] 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[6] cylinder with mu-metal endcaps. Inside the shield, wound on a 12" diameter (split)

[4] Thorlabs PDA36A

[5] Thorlabs FB 800-40

[6] Mu-metal is a special 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.

aluminum cylinder, is a 27.75" long solenoid consisting of 1064±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 1Ω 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[7] generators. Typical modulation rep rates are 10-100 Hz. Start with about 21 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[8] energized 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

[7] Stanford Research Systems. Model DS345. 30 MHz Synthesized Function Generator.
[8] Kepco KS-60-20M

a Hewlett Packard platinum film thermometer.[9] The temperature probe may be 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[10] is a phase sensitive detector. It multiplies the input by a reference, then integrates the result. Whatever component of the input has the same frequency and phase as the reference gives a nonzero integral if the integration time is at least one period of the modulation. The integrator output is amplified and is available at the output on the lock-in's front panel. Analog and digital meters 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.

LabVIEW vi

A virtual instrument called "Scan FM Drive.vi" has been built using LabVIEW to measure the linewidths of the optical pumping resonances. The vi steps the frequency of one of the SRS synthesizers while measuring voltages from both Fluke multimeters[11] 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.

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 synthsizers 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.

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[9] HP 2802A Thermometer.
[10] Stanford Research Systems SR510.
[11] Fluke 8840A

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[12] or a short-wave transmitter.[13] 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)
Rb^{85}	5/2	3037.730
Rb^{87}	3/2	6834.681
H	1/2	1420.405761
D	1	327.384
N^{14}	1	26.12721
		15.67646
N^{15}	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 Rb^{87} and Rb^{85}.
- Determine the nuclear spin of Rb^{87} and Rb^{85}.

[12] 7,500 VAC "neon sign" transformer; the output is controlled with a variac on the primary
[13] Viking Challenger 6 to 80 meter band transmitter

- 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_o gradients.
- Observe diffusion through B_o gradients.
- Study diffusion through the light beam as a function of buffer gas properties.
- Measure the spin exchange relaxation rate for $^{85}Rb - ^{87}Rb$.
- Compare the lineshapes of rubidium resonance in paraffin-coated cells to buffer gas cells.
- 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 N^{14} and N^{15}.

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