Compendium of concepts you should know to understand the Optical Pumping experiment. \

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What follows is specialized to the alkali atoms, of which $_{37}$Rb is one. The ground state of $_{37}$Rb is an S-state (electron in 5s orbit), with S=1/2, L=0; the first excited state is a P-state, (5p orbit) with S=1/2 and L=1. The total spin in these 2 states is **J**=**L**+**S**, i.e. J=1/2 and J=1/2, 3/2, respectively.
Each one of the excited (P-) state is split by the Fine Structure interaction (FS) due to the magnetic field generated by the electron in orbit (if L≠0), and the magnetic moment of the electron, μ: the splitting energy E_{FS}, corresponds to L and S parallel or antiparallel, and is therefore also called LS splitting or coupling; this splitting is proportional to the Fine Structure constant α^2, with α~1/137. The FS splitting is typically 10^{-5} times the P to S transition energy. In Rb the d-state splits into $p_{1/2}$ (lower energy) and $p_{3/2}$ (higher energy).

In Rb the nucleus carries spin I=3/2 or 5/2, (A=87 and 85) and has a magnetic moment μ_I. The total angular momentum of the atom is therefore **F**=**I**+**J**=**I**+**L**+**S**; the EM interaction between the I and J magnetic moments produces the Hyperfine Structure, separating the states with F-values between |I-J| and I+J. In the isotope ^{85}Rb, I=5/2, and the possible values of F are 2 and 3; in ^{87}Rb, I=3/2 and therefore F= 1 (lower) and 2 (higher). This hyperfine splitting (HFS) is 10 time smaller than the FS splitting.

In the presence of an external field, the F-states split into as many states as possible orientations of the vector **F** with respect to the magnetic field vector **B,** the Zeeman splitting; these sub-magnetic states have projections of the F quantum number along the B-direction M, with $-F, -F+1\ldots-1\leq M\leq+1\ldots+F-1,+F$. In a weak B-field and in good approximation, the splitting is even, (i.e. the same energy splitting for all sub-magnetic states of one multiplet), but its value depends upon the atomic and nuclear magnetic moments. At low field the splitting is proportional to B. At high field it obeys the Breit-Rabi equation, see figure 2B-3 in the TeachSpin (TS) manual.

Suppose you irradiate Rb with circular polarized light of a wave length distributed around the energy of the $S_{1/2} \rightarrow P_{1/2}$ excitation energy (light produced in a Rb discharge tube, passed thru a color filter, and a polarizer consisting of a Polaroid film and a ¼-wave plate); right (left)-handed circularly polarized light carries 1 unit of angular momentum, ΔM=+1 (or ΔM=-1), respectively, and can only induce transitions with such a difference of M-value; these transitions are electric dipole (E1) in nature, and only occur between states of opposite parity (as are the S and P states). The ground state is an S-state (positive parity), and the first excited a P-state (negative parity).

Right handed light parallel to the external magnetic field, will induce all the transition seen in Fig. 1. Notably absent is any excitation starting from the M=+2 state in the ground state (in red in figure); **that is the cause of optical pumping**.

Following excitation, the levels return to any of the states in ground state mutliplets, which obey the selection rule being ΔM=±1; including the M=+2 state. After a few tens of millisecond, all levels in the ground state are depleted (empty), and the M=+2 state is (over) populated; as there are then no more excitations possible, the medium has become (relatively) transparent. The medium has been pumped into one state, with M=+2. Note that if in fact the incident light had been left-handed instead, it is the M=-2 state which would have been populated; the difference is not observable here.

So this is pumping the ground state into one state; it requires a magnetic field, and circular polarized light.

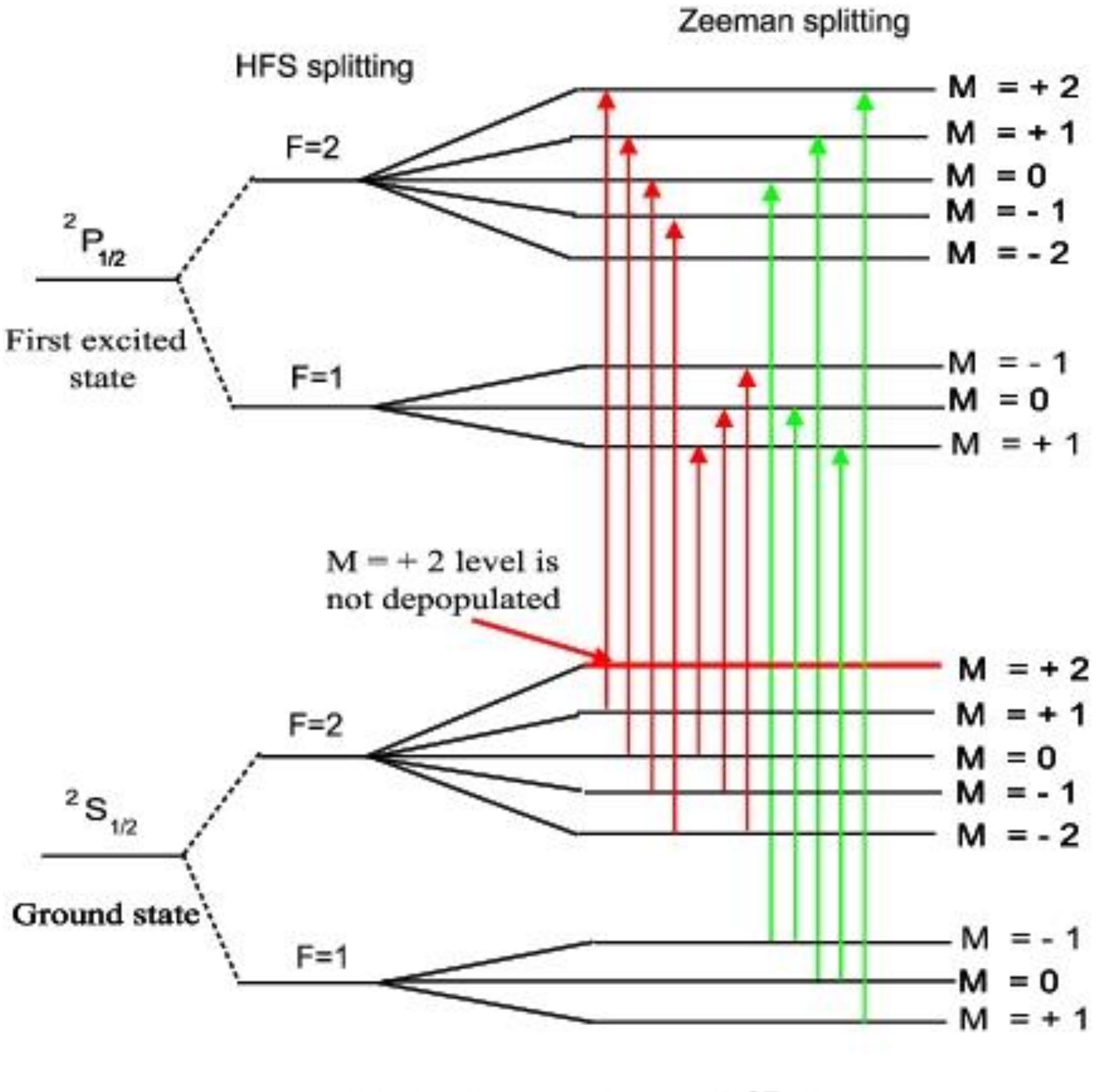
The easiest way to see if pumping has occurred is to de-pump (if the word exists); that will happen if one turns off the external magnetic field, because then no direction is defined along which the spins can orient themselves. The loss of optical pumping is seen as a narrow dip around B=0. No RF is applied, and the field is swept with the “sweep B-field” (axis along direction of light beam) around B=0 if the “start field” is not zero; in fact the earth field is not negligible, and the sweep can be adjusted so that cancellation occurs in the middle of the sweep range; the start current and the current range are adjusted with 2 potentiometers.

If you then apply an RF signal to the coils perpendicular to the apparatus axis, you will also see two smaller lines left and right from the zero field dip; they are Zeeman lines in this very weak field, when the level splitting is very small, and only one dip is seen for each isotope, of course both on the left and on the right of the B=0 dip; they correspond to ground state to first excited state transitions; they are seen as a weak de-pumping of the M=+2 state. From the field values for these 2 dips the ratio of the g_F gyro-magnetic factors can be determined; it is 3/2, but you will want to demonstrate that

from the information in the TS manual! Look at TeachSpin (**TS**) manual, chapter 2, for relevant equations, for g_J, and g_F, and the energy relation. This is what is called “determine the spin of the 2 Rb isotopes” in the manual. Only **the ratio** of g_F (^{87}Rb)/g_F (^{85}Rb) needs to be obtained.
From this part you should learn about FS, HFS and Zeeman splitting in an external field, and E1 transitions from the ground state to the first excited state of Rb s →p transitions.

In very low B-field, ~0.1 G, Zeeman levels are split, and the splitting within one F-multiplet is uniform (constant spacing). At larger fields (several G), the split becomes uneven; see Fig. 2B3 in TS manual (or a better figure generated by Prof. Kossler some time ago. This can be seen and measured by inducing transitions between the levels of an F-multiplet, with an RF Electromagnetic (EM) wave oriented perpendicular to the main field axis. Such a radiation field will induce transitions with $\Delta M=\pm 1$ (hence not $\Delta M=0$), as expected from M1 transitions between states of the same parity. Any one of these transitions disturbs the pumped state; they are seen as a decrease of the transparency (a dip in the transmitted light).
You can find the group of transitions in both isotopes, at a fixed frequency by changing the B-field, or at fixed B-field by changing the RF frequency. You should monitor the RF amplitude with a scope and keep it small (0.2 to 1 V); About of third of maximum amplitude on the RF generator); at higher power a number of additional dips appear (due to higher hamonics) which we will not have time to study in detail here.
Figures 4C-1 and 4C-2 for ^{87}Rb, and 4C-4 and 4C-5 for ^{85}Rb in TS manual show you what you should observe and the corresponding interpretation, i.e. the transitions involved. The separation between the dips increases with the RF frequency.
From this part you should learn about Zeeman splitting in “strong” fields and M1-transitions.

How to get started: part 5 in the TeachSpin manual discusses all the steps you could take to get the setup wired, connected, and aligned; for lack of time you may not want to do all the fine adjustments proposed; you will find the setup producing circular polarized light, with vertical earth field component more or less compensated, and oriented along the horizontal component of the earth field. You can change all of that to convince yourself that it is close to the best. How well aligned affects the width of the B=0 de-pumping dip. You are welcome to try to minimize this width, or to improve the degree of polarization of the light beam, following instructions



Optical pumping of ^{87}Rb

CFP Feb. 9, 2009 opticalpumping_87Rb.pdf

Proposed goals of the experiment and organization of your work

1) Understand the atomic structure of hydrogen like atoms (alkali) like Rubidium; with 1 electron is the nS shell, principal quantum number n=1,2,3,4,5…(5 for Rb).
2) Understand the level structure of the Rb isotopes: Fine structure splitting, hyperfine structure splitting, Zeeman splitting in an outside magnetic field.

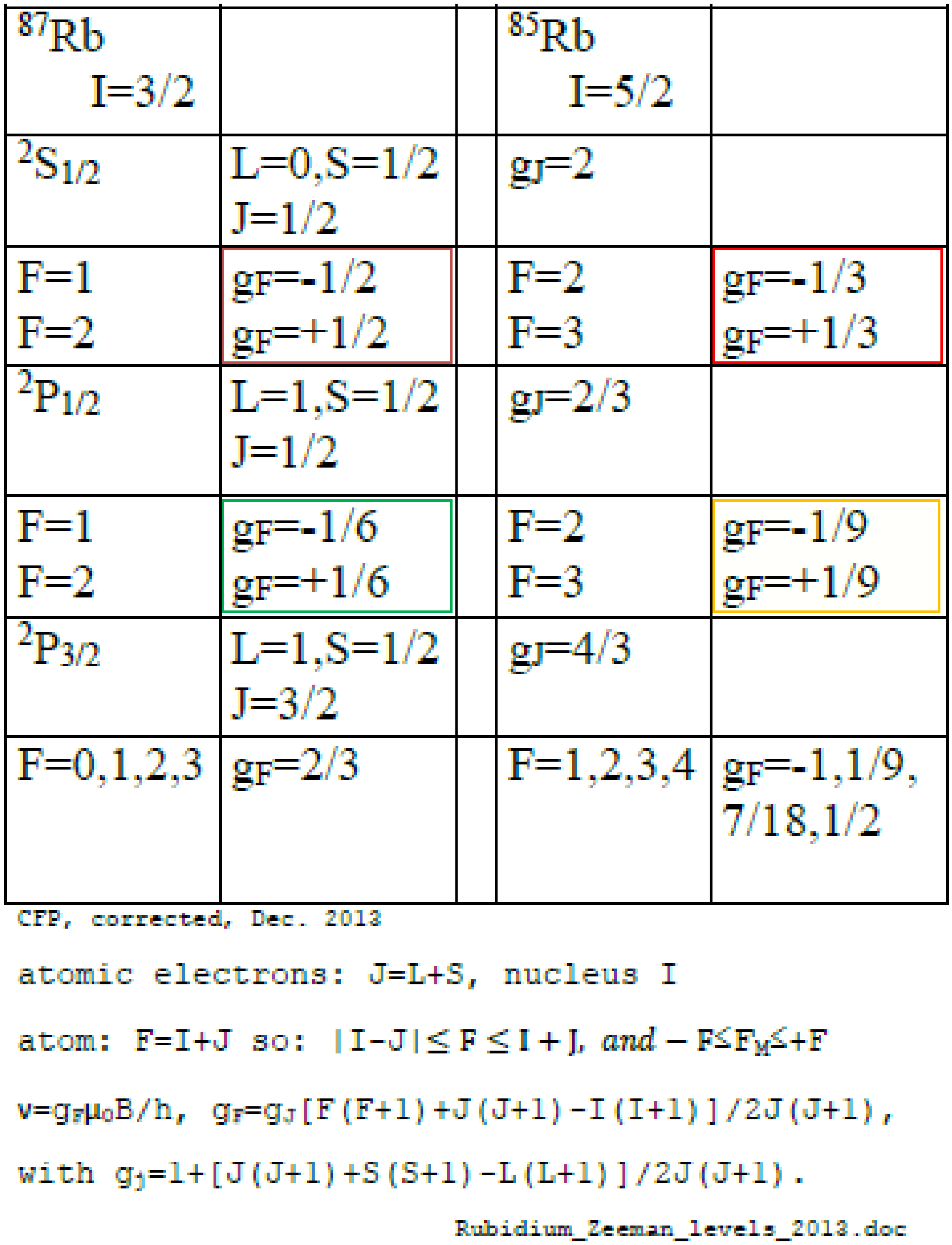
Then understand optical pumping by polarized light, and how an observable perturbation of the optical pumping state can be produced by an external RF electromagnetic wave perpendicular to the polarized photon beam, with frequency the kHz to MHz range.

3) Familiarization with the apparatus. Yes play with all functions and observe the consequence. But **watch for possible overloads**: the current for the main B-field is limited; an overload warning by a red light on front plate of control unit will attract your attention.
   The temperature control gets out of range from time to time: temperature display becomes red, or displays meaningless numbers. Turn off units for 10-20 seconds and it will recover.

4) First observable effect: proof of existence of pumped state. Optical pumping is produced by circularly polarized light of the wavelength necessary to induce transitions from the 5S- to the 5D states of Rb, in the presence of a B-field along the direction of polarization of the light. Selection rules for EM transitions result in all states being depopulated except one; the atoms are then polarized (in a given sub-state of M_F). The light transmission is then maximum. To see that this occurs, sweep the B-field around B=0: you will see a sharp dip at B=0. The width of this dip will be minimum when the apparatus is aligned with the horizontal component of the local earth B-field, so it can be cancelled by the sweeping field; the vertical component can be cancelled by the vertical B-field available. Minimizing this width is the first task.
5) Note that the maximum sweeping field is in the range 1-2 Gauss, and the main horizontal field can reach 7.2 Gauss. As noted in the introduction, fields larger than a few tenth of Gauss produce non–linear Zeeman splitting, i.e. splitting not uniform within a multiplet, and not simply proportional to the B-field applied.
6) Next observe Zeeman splitting by applying a weak field (20<B<250 kG) and following the evolution of the two additional dips (both left and right of the zero-field dip, using only the B-field sweep.
7) By systematically increasing the RF frequency, starting from 10-20 kG, you will see the doublets move towards larger B-field values. Plotting this behavior will determine the ratio of the Rb87 to Rb85 g_F factors (with respectable accuracy). It is close to ½ divided by 1/3!
8) As shown in the table below, the g_F for the ground and first excited state of 87Rb are ½ and 1/6, and for 85Rb they are 1/3 and 1/9,

respectively. This information should allow you to find the corresponding 4 resonance conditions, as g_F determine the frequency (in Hertz) versus the B-field (in Gauss). You may want to start with the highest frequency possible with this apparatus (4.9 MHz) and find the corresponding de-pumping signal for a B-field near 7 Gauss (0.4 volt on the 0.5 Ohm shunt). The others should then be easy to find. You will notice that each one of these resonance has a structure, with 6 to 12 dips. The pattern can be improved by adjusting the amplitude of the RF signal (monitor it with a second scope). Trying to count the actual number of dips is not trivial. Figures 1.10-11, . and 1.13-14 in the man10.pdf will help you understand what you are seeing.

9) Your report should have an abstract and contain tables (and figures if appropriate) of all data you obtained, a discussion of the observation versus the physics, and a conclusion.



^{87}Rb I=3/2			^{85}Rb I=5/2	
$^2S_{1/2}$	L=0,S=1/2 J=1/2		$g_J=2$	
F=1 F=2	$g_F=-1/2$ $g_F=+1/2$		F=2 F=3	$g_F=-1/3$ $g_F=+1/3$
$^2P_{1/2}$	L=1,S=1/2 J=1/2		$g_J=2/3$	
F=1 F=2	$g_F=-1/6$ $g_F=+1/6$		F=2 F=3	$g_F=-1/9$ $g_F=+1/9$
$^2P_{3/2}$	L=1,S=1/2 J=3/2		$g_J=4/3$	
F=0,1,2,3	$g_F=2/3$		F=1,2,3,4	$g_F=-1, 1/9, 7/18, 1/2$

CFP, corrected, Dec. 2013

atomic electrons: J=L+S, nucleus I

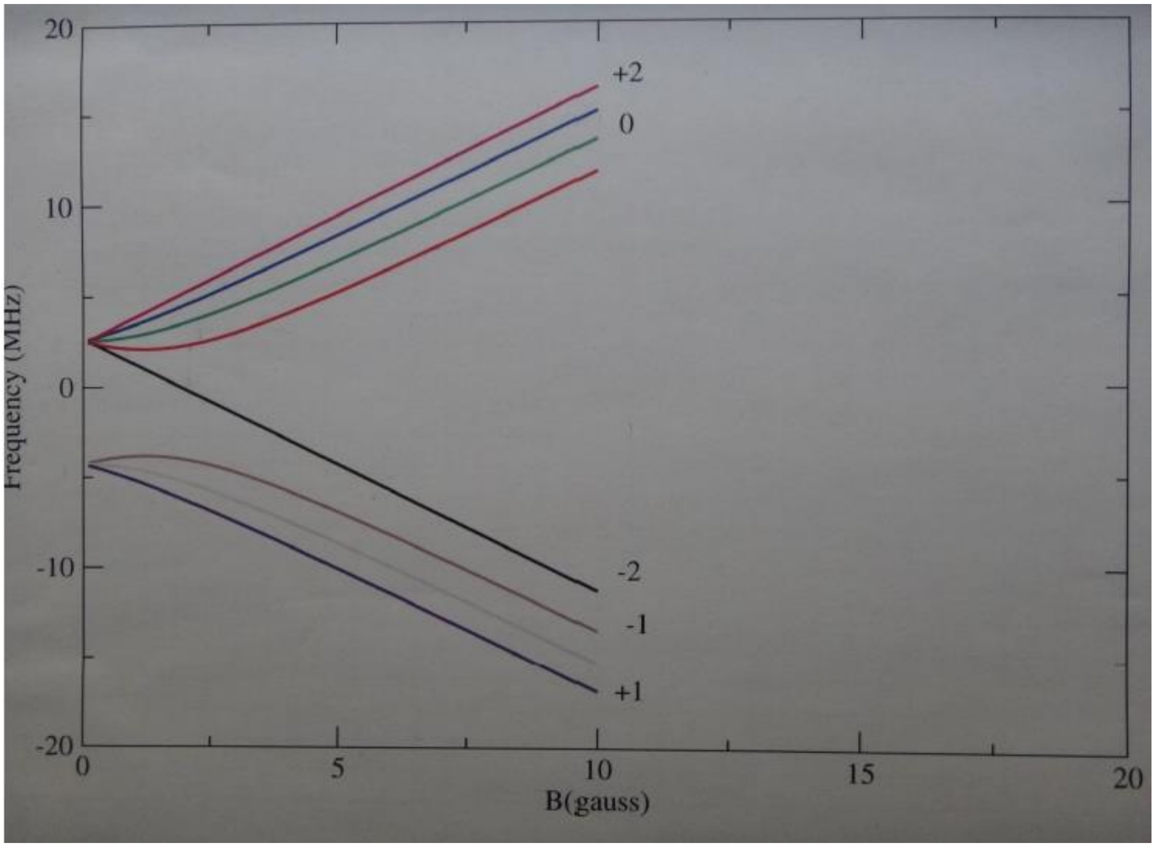
atom: F=I+J so: $|I-J| \leq F \leq I+J$, *and* $-F \leq F_M \leq +F$

$\nu = g_F \mu_0 B/h$, $g_F = g_J[F(F+1)+J(J+1)-I(I+1)]/2J(J+1)$,

with $g_J = 1+[J(J+1)+S(S+1)-L(L+1)]/2J(J+1)$.

Rubidium_Zeeman_levels_2013.doc

Atomic notation: $^{2S}L_J$. Here L=0 is S, L=1 is P, L=2 is D and L=3 is F; these are the original name of the shells: S,P,D, and F.



Zeeman splitting from Breit-Rabi edquation, for 87Rb,
(calculated by Prof. W. Kossler).