Forecast:
Optical Pumping
in Your Future
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The Relaxation Times

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Even More Experiments with Optical Pumping

"Making Your Spins Follow the Field"

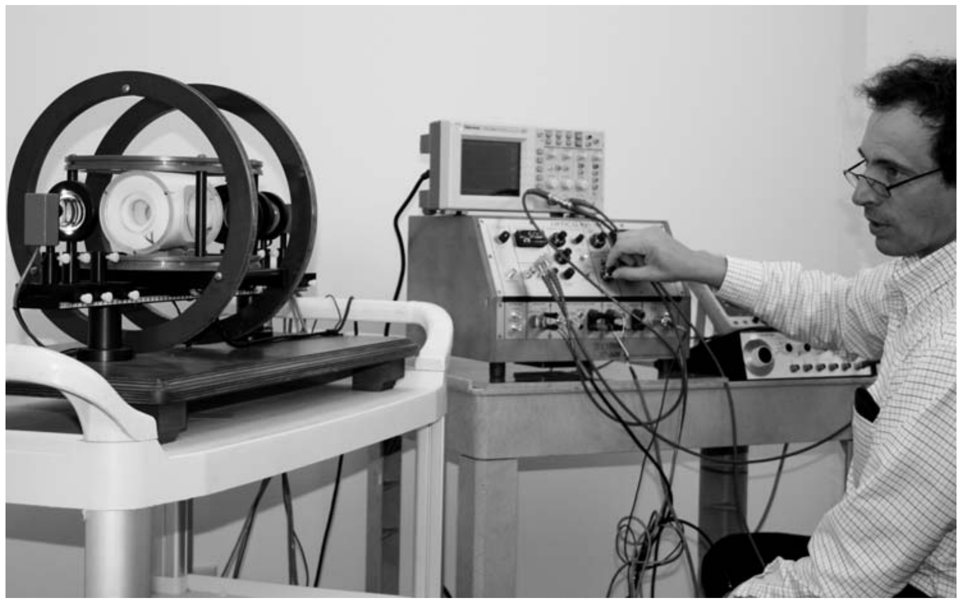

Figure 1: George Herold, Senior Scientist, taking the data used in this report.

Teachspin can only be accused of a little hype when we call our Optical Pumping apparatus "A Course in Atomic Physics". It almost is. A few of its owners have already discovered some of the "untapped" experiments lurking in this apparatus. This entire issue of "The Relaxation Times" is devoted to explaining how, with a ususally available accessory, students can perform an entirely new set of experiments. These open-ended, research-like explorations are appropriate for upper division undergraduate students, as either independent research projects or advanced lab experiments. And the addition of these new investigations certainly is timely! See the feature article in **Physics Today,** Nov. '07, **"The Rubidium Atomic Clock and Basic Research."**

Let's recall the "standard" optical pumping experiment. A rubidium lamp produces a beam of light that is filtered and then circularly polarized before passing through a cell of natural rubidium vapor (and a buffer gas) into a photo-detector. A controllable magnetic field at the cell is applied along the direction of propagation of the beam, which we label the z-axis. The optical pumping signals, due to various perturbations of the system, are simply changes in the light intensity as measured by the photo-detector. These experiments in atomic magnetism are all detected by sensing changes in the transmitted light intensity, not by sensing the very weak magnetism itself.

The experiments that will be described here fall under the category of "rapid" magnetic field manipulation. This "manipulation" is carried out using an ordinary square wave generator whose output is fed into the modulation input of the z-field controller. Using the generator's dc offset control, one can either reverse the z-field, or start at some arbitrary value and rapidly change to another value.

Consider first a set of experiments where the z-magnetic field is reversed. In these experiments, the field is reversed "slowly" enough for the magnetic moments to follow the field but "fast" enough so that the spins do not exchange energy with the surroundings. In the literature, this is called an "adiabatic fast passage". Here are the experiments. The atomic spin system has been allowed to come to steady-state in the circularly polarized light field and in some nonzero z-magnetic field. Now, the z-field is slowly (but not too slowly) reversed, so that it points in the minus z-direction. This is shown pictorially in Figure 2.

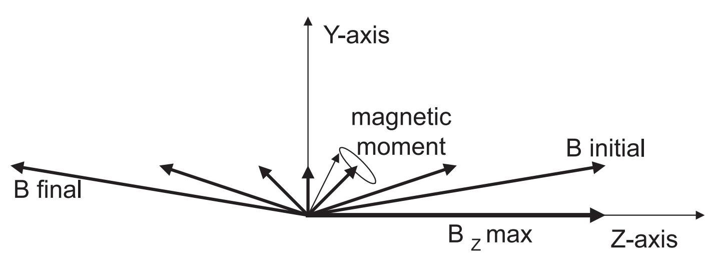

Figure 2

The atoms that were in the weakly light absorbing state, now find themselves in the strongly absorbing states and there is a sudden increase in the light absorbed. (Figure 3)

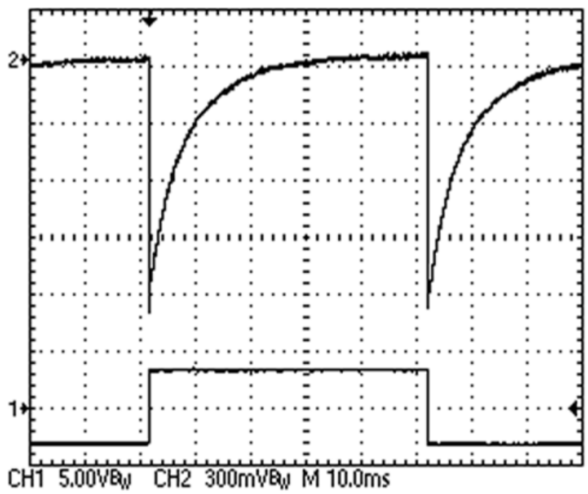

Figure 3

The experimenter can also slow down the rate of change of B_z by shaping the square wave output of the function generator. This can be accomplished with a simple RC network. The rate of change of B_z can be monitored by a pickup coil. Actually, the main B_z field coils can be used as the perfect pickup coil to monitor the B_z field. It is interesting to study these signals as a function of a small residual B_y static field (Figure 4). Note: The signal decreases with decreasing B_y.

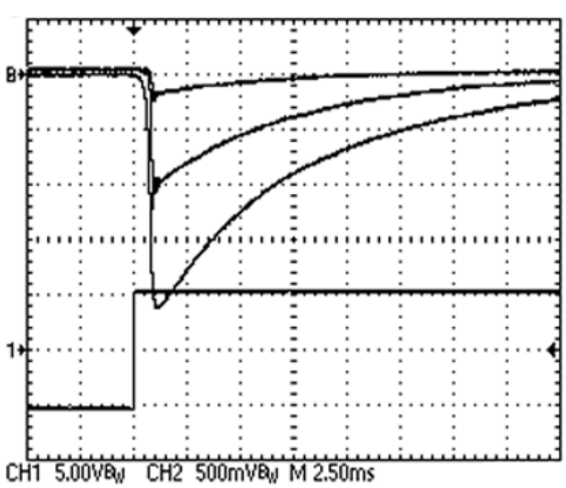

Figure 4

Observant students may notice some transient wiggles on the signals detected in these field reversing experiments. They should study them. These "wiggles" are not instrumental artifacts of the electronics, but "real" physical phenomena. These oscillations come from the spins that were not able to follow the field and end up precessing about the B_y field after the B_z has been reversed.

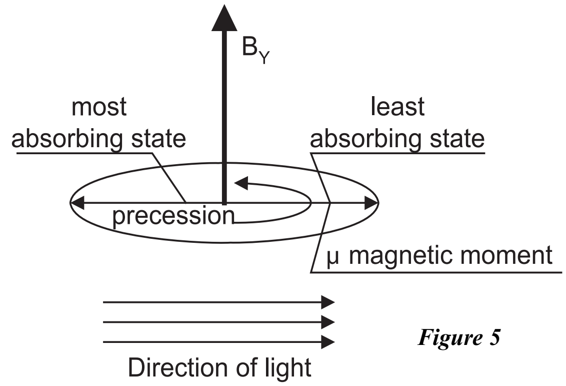

Figure 5

If we are correct about the source of these oscillations, there are some interesting experiments the students can perform to verify the explanation. What enhances these oscillations? Suppose, instead of reversing the B_z field, we drive B_z to zero quickly, but still leave a finite component of B_y. The spins left behind in this experiment undergo free precession about the B_y field.

This precession about the y-axis causes a change in the optical transmission of the cell at the precession frequency. This can be understood by realizing that when the spins are along the z-axis, they are in a weakly absorbing state and when along the –z-axis, they are in a strongly optically absorbing state. The system is oscillating between the two states at a precession frequency determined by the magnetic moment of the atom and by the total field.

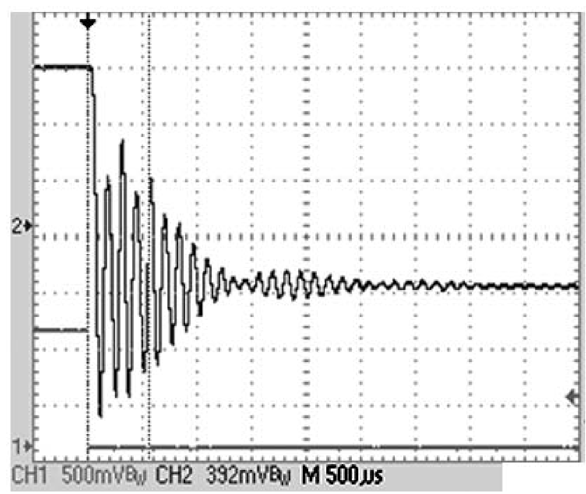

Figure 6

Look carefully at Figure 6. You will notice a beat signal. The amplitude of the peaks alternates. This is, again, "real" physics. It is due to the difference in the magnetic moments of the two kinds of atoms in the sample Rb^{85} and Rb^{87}. But there is also a 'beat signal" which drives the entire signal to zero approximately 1.5 ms after the field step-change. This turns out to be due to the magnetic field inhomogeneities in B_y. The inhomogeneities are due to a combination of the local fields in the laboratory and gradients produced by the y-axis Helmholtz coils.

Using a suggestion by David Van Baak, George was able to tune out most of the B_y gradient. He suspended a permanent magnetic dipole along the y-axis just above the sample and tweaked its location while observing the free precession signal. The improvement in the ring-down time is dramatic, as shown in Figure 7.

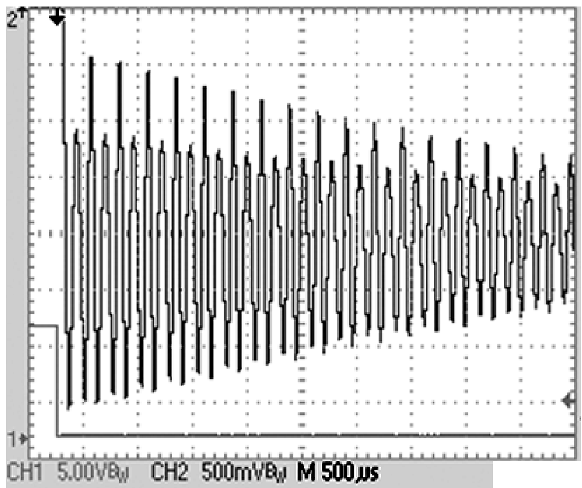

Figure 7

It is instructive to analyze this signal with an FFT, which is now commonly available on digital 'scopes. Figure 8 shows our data. In this case, the oscilloscope shows the signal in the frequency domain, rather than as a function of time. Notice that there are two distinct peaks, with the largest intensity peak coming from Rb^{85}. The ratio of these two frequencies is an absolute measure of the ratio of the magnetic moments of the two atomic isotopes.

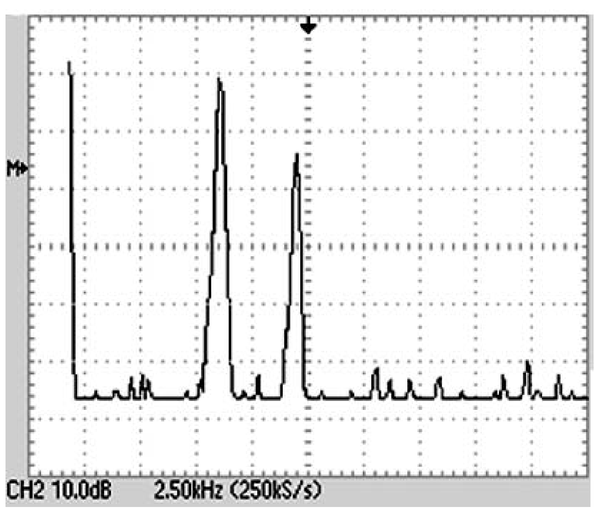

Figure 8

Another precise check on our model is to plot the ring-down frequency (as measured with the FFT) as a function of the B_y field. At these very low fields, however, the local environment creates a fluctuating field that scatters the data points. This distraction was greatly reduced by finding the B_y field that gave the same precession oscillation frequency both above and below the zero field value. Then, one half the difference between these two values was taken as the correct B_y. These data are shown in Figure 9.

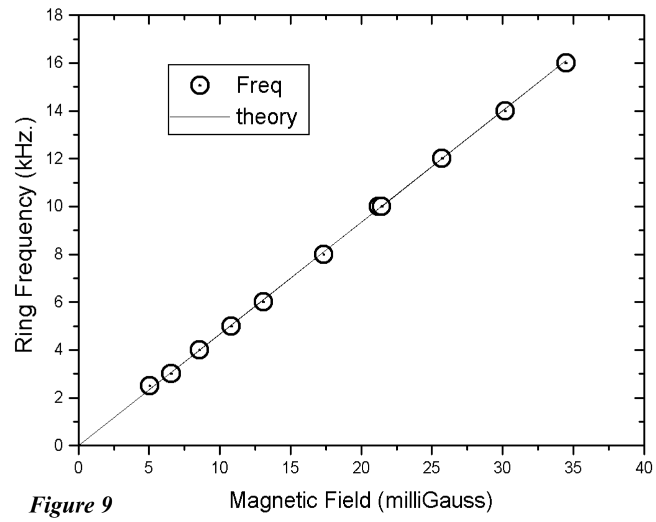

Figure 9

Note that this technique allows the measurement of the atom's magnetic moment without the use of an rf signal generator. These data can be compared with the "standard" methods using the rf spin flips to see if there is agreement. With data of this quality, field changes of under 1 milligauss are easily observed! Remember, the Earth's magnetic field is on the order of 500 milligauss.

The same techniques can be used to study the optical pumping times of the system. Now, instead of examining the response of the system with $B_z = 0$, students will observe how long it takes the system to be pumped to its steady-state at some "large" B_z. This is called the pumping time. First of all, the student should discover that the signal amplitude and time constant is independent of the magnitude of B_z (for $B_z > B_y$). Figure 10 shows the pumping time as a function of light intensity. This time was determined by a single point measurement, assuming an exponential rise and defining the pumping time as the time until the signal reaches 2/3 of its asymptotic value.

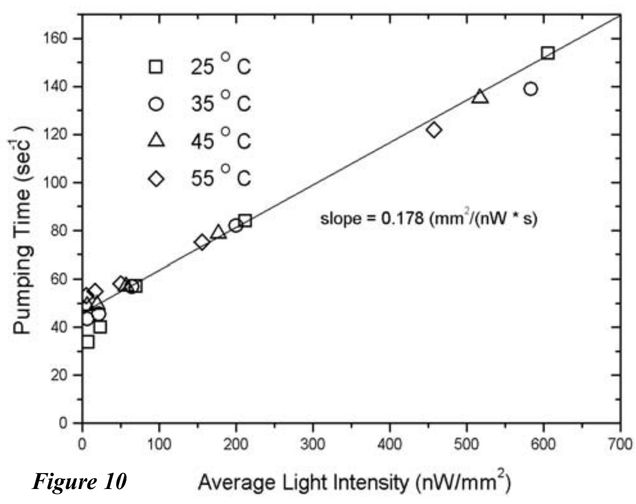

Figure 10

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As anticipated, the pumping rate increases with increasing light intensity. (The more photons impinging on the atoms, the faster the system is pumped.) What was not expected was the behavior at ***low light intensity***. The rate did not tend to zero, but to some constant value. The other interesting characteristic was that, at low light intensity, the signal was proportional to the ***square*** of the light intensity (Figure 11). These data lead us to develop the following simple model of pumping in the ground state.

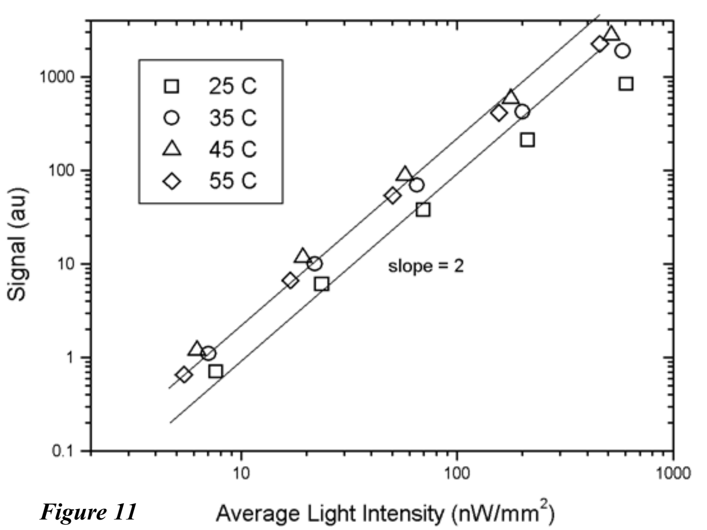

Figure 11

Assume that the ground state can be divided into two classes: atoms in class N_1 are strongly absorbing with absorption probability given by α_1 and atoms in class N_2 are more weakly absorbing with probability α_2. The total absorption probability of the ground state is then given by the average, $\alpha=(\alpha_1+\alpha_2)/2$. We also assume that when atoms decay from the excited state, they have equal probability of going into either N_1 or N_2. And finally, we add some relaxation process that depends on the population difference between the two states, with a rate given by β.

Then, the rate of change in the number of atoms in state N_2 is:

$$\frac{dN_2}{dt}=\frac{1}{2}\alpha_1 I N_1-\frac{1}{2}\alpha_2 I N_2-\beta(N_2-N_1)$$

With $N_1 = N - N_2$ and $N_2\ (t=0) = N/2$ we solve this simple equation to get:

$$N_2=\frac{N}{2}[1+f-fe^{-(2\beta+I\alpha)t}]$$

$$f=\frac{I(\alpha_1-\alpha_2)/2}{2\beta+I\alpha}$$

Note: when $\alpha_1 = \alpha_2 = \alpha$, then the factor $f=0$ and there is no pumping.

The most interesting part of this equation is the factor in the exponential, $2\beta + I\alpha$. This is the pumping rate. At low light intensities the pumping rate is determined by the relaxation process β. And the pumping rate increases linearly with light intensity. This is what we observe. We also see that the relaxation rate tends to increase with temperature, which might be explained by an increase in number of Rb-Rb collisions.

These new experiments significantly expand the already broad "intellectual phase space" of TeachSpin's Optical Pumping Apparatus. It now provides not only a "course" in atomic physics, but also an opportunity for open-ended, research-like undergraduate experience. As noted in the **Physics Today** article, it also has extremely important practical applications.