Forecast:
More Physics
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The Relaxation Times

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Optical Pumping

Beyond the Manual – but Latent in the Apparatus

Even if we leave it out of the manual, we don't leave it out of the equipment! That is to say, our apparatus gets the physics right, and it can illustrate physics that we *hadn't even thought about when we wrote up its description*.

If you've heard of Optical Pumping, or read our 'Conceptual Introduction' posted on the Optical Pumping pages of www.teachspin.com, then you know that this apparatus offers a wonderfully direct way to explore driven, or induced transitions between the quantized energy levels of rubidium atoms which occur when the vapor (which contains both isotopes, Rb^{87} and Rb^{85}) is immersed in a uniform magnetic field.

The transitions that are most easily observed are driven by radio-frequency magnetic fields. They correspond to transitions between energy levels that are sub-states of the atoms' ground-state energy. The transitions that occur at frequencies on the order of 1 MHz are between ground-state sub-levels that have been separated in energy by the uniform magnetic field B in which the atoms are immersed – this is the Zeeman effect.

Calvin undergraduate Nathan Danks observing transmission signals with TeachSpin's OP1

Fig. 1, on the following page, shows how these levels spread as the magnetic field *B* is varied from -5 to about 25 μT while a 100 kHz RF field is maintained across the vapor. For B-fields this small, the Zeeman sub-levels of the ground state levels are equally spaced in energy, so the transition frequency is the same for transitions between any adjacent pair of levels. That transition frequency turns out to be given by:

$$f = 28.0 \left(\frac{kHz}{\mu T}\right) \frac{B}{2I+1} \qquad (1)$$

where *I* is the nuclear spin quantum number.

When the magnetic field *B* passes through zero, the Zeeman sub-levels of both isotopes become degenerate, and we see a dip in transmission of light through the vapor. But there are additional dips at $B \neq 0$, which we attribute to the less-abundant Rb^{87}, and the more-abundant Rb^{85} isotopes. The *B*-values at which these are predicted to occur are given by equation (1). The observed *B*-values of 14.3 μT and 21.4 μT are consistent with nuclear spins of I = 3/2 for Rb^{87} and I = 5/2 for Rb^{85}. (A quick check of the oscilloscope trace shows the expected 4:6 ratio of the magnetic-fields values.)

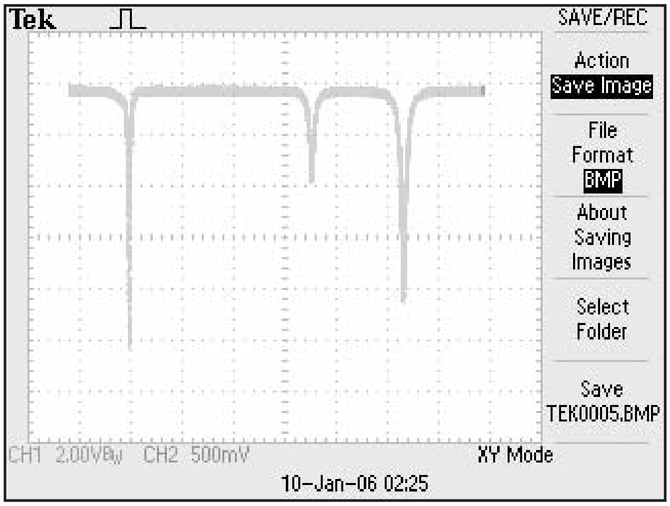


Fig. 1: Transmitted intensity vs. magnetic field with a 100 kHz RF field applied. B varied -5 to 30 µT.

As the RF frequency is increased, transitions will occur at ever increasing magnetic fields. For a frequency of 4993 kHz, our equation predicts a transition for Rb^{85} at $B = 1070$ µT. If we now set the magnetic field at this value and sweep the RF, interesting things happen! We do not get the neat single dip we were expecting.

Fig. 2 shows some traces obtained by holding the field fixed, and sweeping the frequency for Rb^{85}. The single dips, one for each isotope, now resolve into sub-transitions, 4 for Rb^{87} and 6 for Rb^{85}. [Each optical-pumping unit is shipped with a testing document showing the four resolved Rb^{87} transitions, spread out very slightly in *magnetic* field when observed at a transition frequency of $f = 5.0$ MHz.

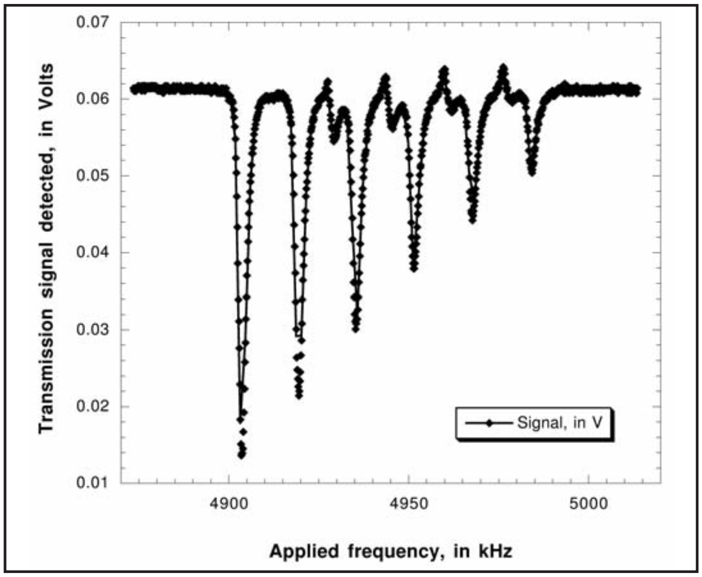


Fig. 2: Resolved structure of the Rb^{85} Zeeman transition. This trace shows a scan over frequency in a fixed magnetic field of about 1070 µT. The separation, δf, between adjacent features is about 16 kHz, and the features are spread about an average frequency $f \approx 4.994$ MHz.

What causes this separation? What can be measured using it? The easiest way to understand the effect is to see that the initially-linear Zeeman shift of the ground-state sub-levels does not continue to be linear at higher field strength B. Instead, the energy levels start to curve, resulting in ***unequally*** spaced sub-levels. For example, in the $F = 2$ hyperfine ground state of the Rb^{87}, there are $2F+1 = 5$ sub-levels with differing m_F-values. Thus, there can be 4 transitions between adjacent pairs of m_F-states. These become four ***distinct*** transitions, readily resolved at large B, because the energy levels are no longer linear in B.

The fact that there are four observable lines for Rb^{87} (or six, for Rb^{85}) is already a direct check on the nuclear-spin assignments – a proof, if you will, of quantized nuclear angular momentum. But there's more! The energies of these levels as a function of field are described by the Breit-Rabi formula, and its predictions can be expanded in powers of the field B. At order B^1, it gives the equal level spacings predicted above. At order B^2, it gives a corrected prediction of the level spacings, and predicts how the transitions will split apart into 4 (or 6) sub-transitions. The spacing between the sub-transitions, δf, is predicted to grow as B^2. It is possible to show that, to a good approximation,

$$\delta f = (2 / f_0) f^2,$$

where f is the average Zeeman frequency, and f_0 is the **ground-state hyperfine-structure splitting.**

Nathan Danks, a physics undergraduate at Calvin College, followed these transitions up to frequencies near 10 MHz. He chose to view them at fixed B-values, scanning over f-values to locate the sub-transitions. A scan over frequency, using a sweepable frequency generator, gives a view of the resolved transitions (shown for Rb^{85} in Fig. 2). The sub-transitions are equally spaced, with δf observed to have value near 16 kHz for the value $f \approx 5$ MHz used here.

Then, plotting his observed δf values as a function of the Zeeman frequency f around which they're centered, Nathan got the plot shown (on log-log scales) in Fig. 3. It does indeed show consistency with the f^2 dependence predicted above.

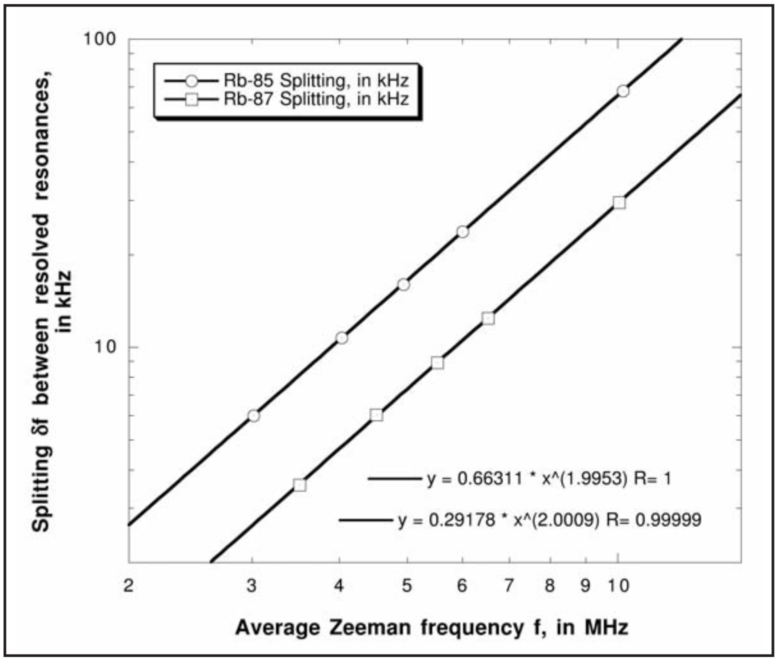


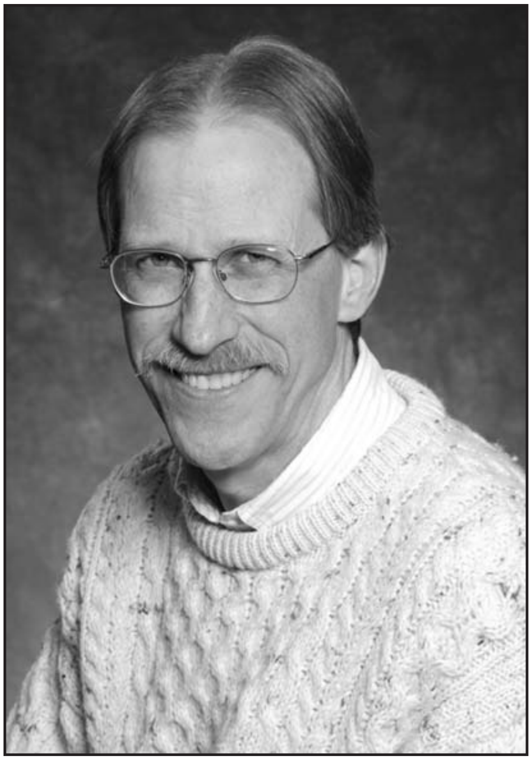
Fig. 3: Dependence of the observed frequency-splitting δf as a function of the average frequency, *f*, at which they are observed, plotted for Zeeman transitions of both Rb^{85} and Rb^{87}.

Furthermore, the coefficient of an f^2 model can be used to extract a prediction of the ground-state hyperfine splittings. Nathan got:

$$f_0(\mathrm{Rb}^{85}) = 3{,}048 \pm 4 \text{ MHz}$$

$$f_0(\mathrm{Rb}^{87}) = 6{,}845 \pm 9 \text{ MHz.}$$

These high frequencies lie in the microwave region of the spectrum, and it would require quite different radio-frequency generators to drive them. TeachSpin is waiting to see which of you will be the first to 'illuminate' your optical-pumping cell with microwaves (of the right frequency and polarization) to drive these transitions directly. These transitions also should have linewidths of only a few kHz (like those in Fig. 2) - but their frequency locations are in the millions of kHz. The motivation is to drive, on a tabletop, the transitions that are actually used in rubidium-stabilized atomic-clock modules (because they are independent of the external magnetic field, to first order). This is the basis of one type of commercial atomic frequency standard, for example Stanford Research Systems PRS10.



Van Baak Named APS Fellow

At the APS April meeting, TeachSpin's collaborating physicist, Professor David Van Baak of Calvin College, was elected a Fellow of the American Physical Society. This prestigious honor is for outstanding contributions to both physics research and education. Nominated by the Forum on Education, David was recognized "for successfully refining and extending experiments used in the undergraduate curriculum and for promulgating the use of diode lasers in the undergraduate laboratory".

Members of the TeachSpin community can easily attest to David's many contributions. You hear his voice in this very issue, describing yet another extension he has found for a TeachSpin apparatus. Our relationship began in 2001 when we converted his "Twiggy's Coffin" version of Two-Slit Interference into the sleek apparatus now a student favorite in so many schools. We don't have the space to enumerate all of the contributions he has made to the expansion and enhancement of TeachSpin offerings. But a careful reading of the manuals might reveal his presence. Hint: look for semicolons that Barbara and Jonathan missed!

And, we are not the only ones benefitting from David's talents. The membership of the Advanced Laboratory Physics Association (ALPhA) has elected him to its presidency. Now let's see what happens when has an organization to run!!

TEACH SPIN

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Immersion Schedule for Summer 2011

visit **www.advlab.org** for full descriptions

WHEN & Where	**WHAT** Experiments will be Done	**WHO** will Mentor
July 20 – 21 **Bethel University** St. Paul, MN	• Imaging of Shock Waves in Flows • Stabilized Laser Diode Experiments • Homebuilt Wavemeter Experiments • Nanoscale Heterodyne Interferometry • Stroboscopic Holographic Interferometry	Chad Hoyt Keith Stein Richard Peterson
August 8 – 10 **Buffalo State College** Buffalo , NY	• Pulsed NMR • Optical Pumping • Modern Interferometry • Mossbauer Spectroscopy • High Temperature Superconductivity	Jonathan Reichert David Van Baak Mike DeMarco Ram Rai
August 10 – 12 **Caltech** Pasadena, CA	• Saturated & Resonant Absorption Spectroscopy • Thin Film Deposition & Vacuum Techniques • Low Noise Signal Detection with Lock-Ins	Eric Black Ken Libbrecht
August 15 – 16 **Reed College** Portland, OR	• LabVIEW Instruction for the Advanced Lab	John Essick
August 15 – 17 **Colgate University** Hamilton, NY	• Quantum Eraser • Biphoton Interference	Enrique ‘Kiko’ Galvez
August 18 – 20 **Rochester University** Rochester, NY	• Entanglement and Bell’s Inequalities • Single-Photon Source	Svetlana Lukishova