Forecast:
photons,
rf to NIR

The Relaxation Times

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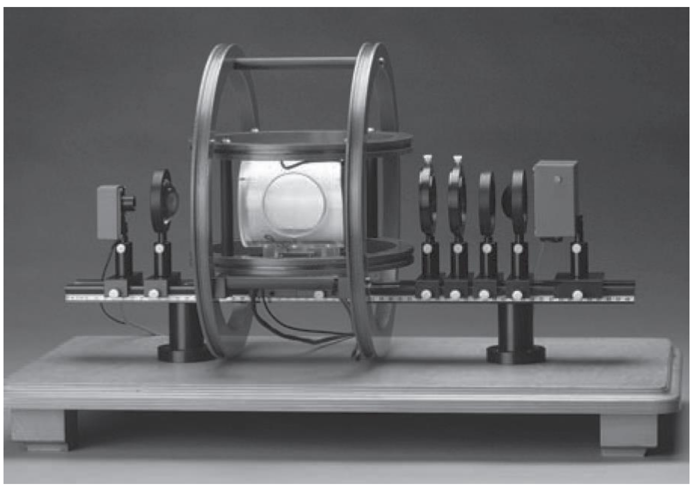
A Journey of Discovery in Quantum Physics

Table-top Exploration of 2- and 3-Photon Transitions With TeachSpin's *Optical Pumping* Apparatus

Optical Pumping was purposefully designed to provide a 'wide intellectual phase space'. It offers a combination of electronic and optical components that, with some faculty encouragement and a bit of direction, invite the student into the kind of highly independent exploration that we like to call an ***investigative experience.***



At TeachSpin, we sometimes think of the Optical Pumping apparatus as a 'quantum sandbox' in which students can play and learn. Past issues of the **Relaxation Times** have reviewed many of the quantum-mechanical phenomena they can explore with this device, including:

- Hyperfine interactions in rubidium atoms
- Zero-field transitions
- Rabi oscillations
- Optical pumping times
- Field-reversal experiments
- Coherent population trapping

This newsletter describes yet another quantum process that can easily be introduced to students and that, in the process, can provide a genuine ***investigative experience.*** This kind of exploration is different from asking students to verify a theory or model that has been introduced to them in advance. Rather, we think it is a model of what drives much of physics research, where *discovery* can be as important as *measurement*. Once engaged, students can follow clues, choose parameters, look for patterns, find relationships, and even recognize the kind of 'pre-discovery observation' often noted in astronomy. That's the educational philosophy – now let's talk about the actual experiments.

Consider the option of driving transitions between adjacent levels of the five Zeeman sublevels of the upper hyperfine level of the ground state of ^{87}Rb. At low magnetic fields, four such transitions overlap. At intermediate values of the dc magnetic field, however, the four transitions become resolved. For example, the four 'lines' can be observed by slowly scanning the dc magnetic field B_Z over a small range centered on 715 μT (7.15 gauss). This is done while driving the transitions with a sinusoidal radio-frequency magnetic field $B_X(t)$ with a frequency f fixed at 5.00 MHz, and *with an amplitude that can be chosen by the student.* For small values of the amplitude of the imposed rf magnetic field, the transition probability observed during a scan of B_Z displays the lovely four-line pattern as shown in Fig. 1.

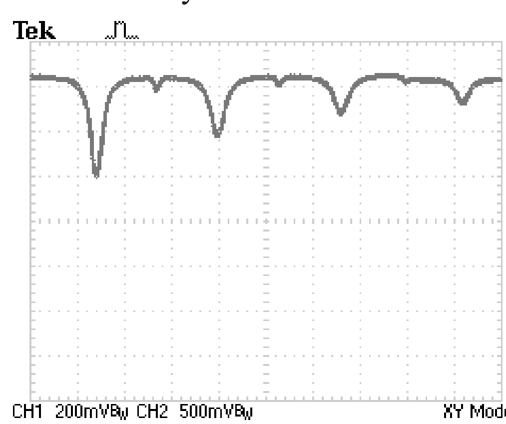


Fig. 1: The optical-transmission signal from our optical pumping apparatus, plotted for a sweep of the static magnetic field B_Z from 713 to 717 μT, when an oscillating field B_X of small amplitude and fixed 5.0-MHz frequency is applied.

Of course, there is plenty of 'spectroscopy' that can be done with transitions such as these, and past newsletters have described some of it. But the new question, one that can launch students on a 'journey of discovery', is: **how do the *heights* of those transition peaks vary with the strength of the oscillating magnetic field B_x that is driving them?** Thus, students are directed to focus on the peak heights and line shapes in the spectrum, instead of considering only on the location of those peaks in frequency (or magnetic-field) space.

These experiments are considerably enhanced by the availability of new, and very affordable, digital signal generators, such as the Rigol DG1022, which offers great frequency stability and well-controlled and stable output amplitude. In addition, the Rigol can provide large output amplitudes without harmonic distortion. All of these characteristics **matter** in this set of experiments.

What will the students discover? (if you let them!) At *low* amplitudes of the radio-frequency drive, these fully-allowed magnetic-dipole transitions are expected to have probability-amplitudes that are linear in B_x, so the transition probabilities should grow as the square of the amplitude of the perturbing magnetic field, and hence as B_x^2. This is easy to verify – but already here there'll be novelties to discover, since at larger values of B_x, the phenomena of saturation and power-broadening will become apparent.

And changes more dramatic and unexpected than mere saturation will also appear in the four-line pattern.

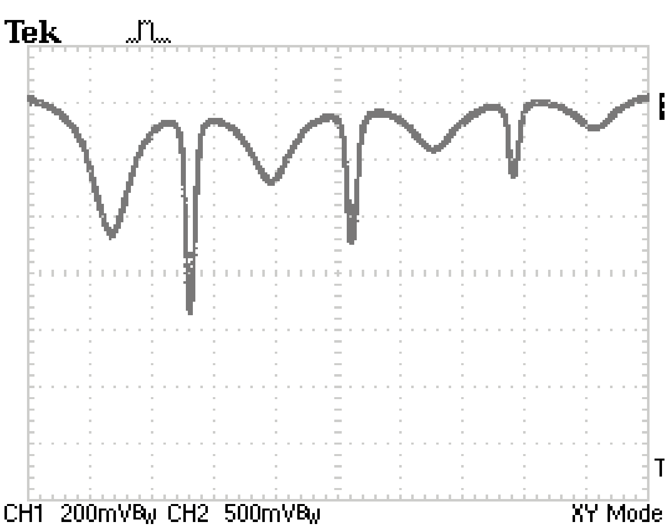


Fig. 2: The optical-transmission signal (as in Fig. 1) for the same magnetic-field B_z sweep, when an oscillating field B_x of larger amplitude, but having the same 5.0-MHz frequency, is present.

As Fig. 2 shows, in addition to a broadening of the previous observed four lines, unexpected features manifest themselves at intermediate locations in the scans done over the four-line pattern.

The new features are narrow, and their heights grow rapidly with increasing values of B_x. (Now you can look back and see their precursors in Fig. 1, as well. There's a 'pre-discovery observation' for you!)

These new features can be attributed to **two photon transitions**, where by 'photons' we are referring to the photons of the 5-MHz rf magnetic field. The explanation of their location can be most easily understood by considering a three-level quantum system as represented in 'cartoon' fashion in Fig. 3.

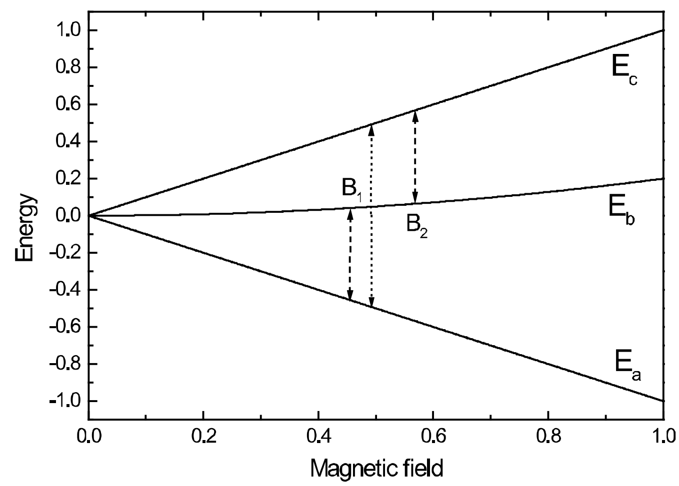


Fig. 3: A 'cartoon' of three Zeeman levels, showing energies as a function of static magnetic field B_z. Vertical lines indicate the two single-photon and one two-photon transitions that can occur.

Under these conditions, two allowed single-photon transitions can occur where

$$hf = E_b - E_a \quad \text{at field } B_z = B_1,$$

and $$hf = E_c - E_b \quad \text{at field } B_z = B_2.$$

But quantum mechanics also permits a two-photon transition, occurring at condition

$$h \cdot 2f = E_c - E_a .$$

This transition will show up at an intermediate tuning-field value that is, in fact, very near $B_z = (B_1 + B_2)/2$, halfway between the features previously seen at fields B_1 and B_2. That explains why the new features shown in Fig. 2 arise midway between the previously-seen single-photon transitions.

What is expected for the *strength* of these new transitions? The probability of such a transition is predicted to vary (in lowest order) as B_x^4 instead of B_x^2. Again, this dependence can be discovered by the students in a straightforward way. Fig. 4 shows some actual data on the strength of one of these two-photon features.

As is the case with the single-photon transitions, these two-photon transitions also exhibit saturation and broadening at higher strengths of the oscillating field. But there is still more! For the actual case of ^{87}Rb, where there are not just three but five Zeeman levels, students can also discover *three*-photon transitions. And for these transitions, the strength grows not as B_x^2 nor as B_x^4, but instead as B_x^6 in early stages, before they in turn saturate. The lines added to Fig. 4 display the 4th- order and 6th-order power-laws that describe the initial rates of growth of these transition probabilities.

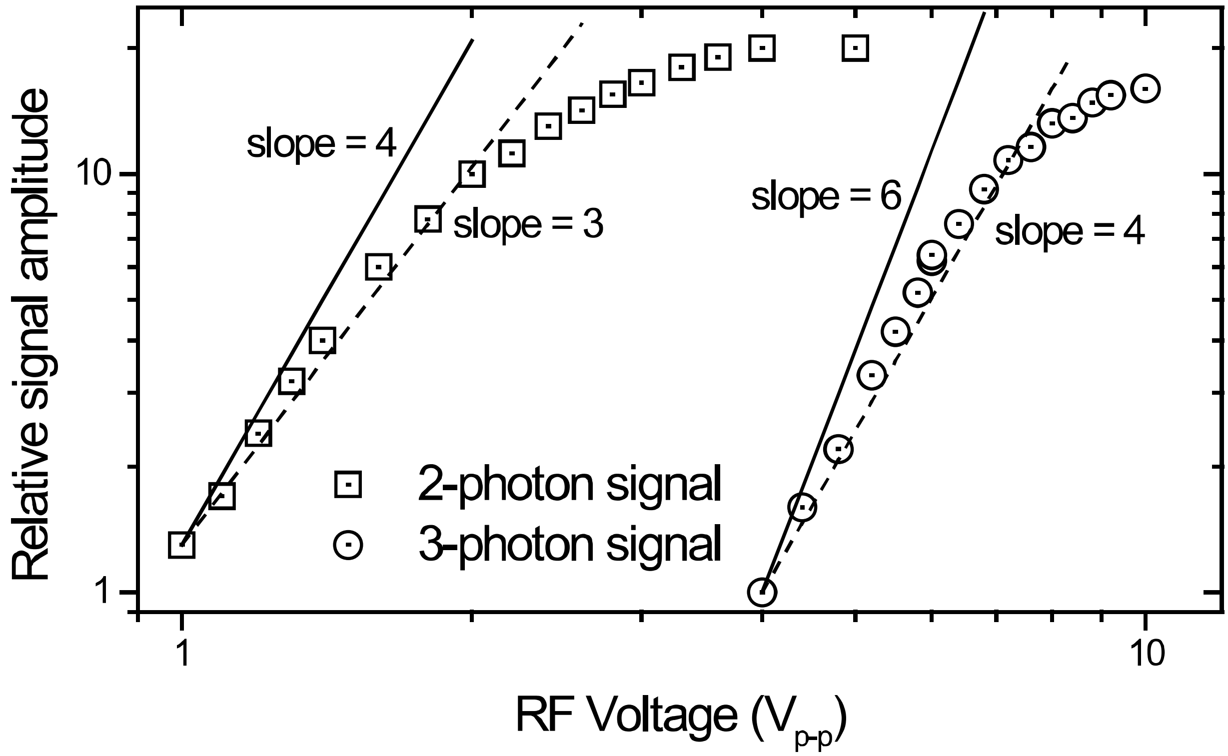


Fig. □: Height of a two- □and a three-□photon transition, as a function of the strength of the oscillating field B_x, shown on log-log scales. The □ertical axis is in ar□itrary units. The o□erlay of lines for □th- order and □th-order power-law dependencies show the initial growth rates of the heights of these multi-photon transitions.

Clearly, there is a lot more quantum physics going on here than ever gets covered in the usual textbook treatment of the lowest-order time-dependent perturbation theory! There would be a thesis-full of work in the detailed theoretical calculation of locations, strengths, and line-shapes of this panoply of spectral features. But that's not our point – we want to emphasize that the quantum-mechanical behavior of the rubidium atom, as it is captured in this apparatus, can lead students to discover features for which they are not prepared. Furthermore, the apparatus will give the correct experimental answers every time, without calculation and without ambiguity; and it gives those answers repeatedly and rapidly, for each fresh sweep through the spectrum of transitions. Your students can ***discover*** real-time quantum-mechanical answers to questions rarely even posed, and certainly never answered, in class.

There was a time when two-photon (or double-quantum) transitions were an exotic theoretical possibility, to be invoked only in the case of highly forbidden spontaneous decays (as in the 2s → 1s decay in atomic hydrogen). More recently, the experimental task of driving two-photon optical transitions was the natural preserve only of those with access to high-power lasers. But in the radio-frequency regime accessible to users of our Optical Pumping apparatus, two- and three-photon processes are easily-accessible everyday realities. We're happy to bring these formerly exotic and research-level phenomena into the advanced lab, and we hope your students too can enjoy this kind of ***investigatory experience*** of discovering them.

TEACH SPIN

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Recruiting for a new position at TeachSpin: Sales and Marketing Director

Here's the text of a classified advertisement that will soon appear in *Physics Today*:

A small tight-knit company (that's us) is looking to hire an experimental physicist, preferably one with teaching experience, who enjoys people, playing with apparatus, travel, and schmoozing with faculty about teaching. As sales and marketing manager, this person will be expected to operate, understand, and be able to explain to both faculty and students every instrument in our catalog. We expect this person to make a significant long-term contribution to the development of our company. A minimum of an M.S., but preferably a Ph.D. in experimental physics is required. Send resume to JFReichert@teachspin.com.

Dramatic changes at TeachSpin

Big changes are occuring here at TeachSpin. Jonathan Reichert has created a not-for-profit 501(c)(3) foundation whose mission is to "Enhance Advanced Laboratory Instruction", and has gifted the for-profit corporation TeachSpin, Inc. to the Foundation. Although the details of this transaction are complicated, he believes that this new arrangement is the best way to ensure the long-term viability of TeachSpin. The new Foundation will **also** support advanced-laboratory instruction in many different ways. For details, please check out the Foundation's website, www.JFReichertFoundation.org.