

Hyperfine Spectrum of Rubidium: laser spectroscopy experiments

Physics 480W
(Dated: Fall 2015)

I. PERSPECTIVE AND OBJECTIVE

There are several interwoven themes in this experiment, although I will choose just two: laser spectroscopy and nuclear spin. The former has proved to be a very practical tool for a broad range of scientists, quite outside the pale of physics even, and the latter, while eventually leading to enormously practical technologies as well (e.g., think MRI, or even atomic clocks), was a remarkable quantum discovery, and goes back to Rabi's work on the molecular beam method of measuring nuclear magnetic moments before WWII, and to Pauli's recognition that there should be such things in nature before that. I say the themes are interwoven because the 1981 noble prize in physics was shared by the physicists who first developed laser spectroscopy, and who made spin-physics discoveries in nuclei and with electrons. One of these physicists (Nicolaas Bloembergen) did both things really, and there is a line that runs from his work with nuclear resonance straight through Norman Ramsey's work, and Ed Purcell's work, to Rabi's work. One of the common themes is the experimental question: how to observe transitions between states each of which are split by nuclear magnetism, especially when there are confounding effects that make observation difficult? High resolution optical spectroscopy, made possible with very coherent, narrow bandwidth laser light (along with a few important experimental tricks) makes such observations possible, thus making manifest the effects of nuclear magnetism upon atomic energy states.

What are we attempting to observe? We want to see transitions between the ground state of Rb I to its *second* excited state, $^2S_{1/2} \rightarrow ^2P_{3/2}$, given that within these two terms there is hyperfine structure, a very, very small energy perturbation compared with the energy gap between the two terms...and we want to see the underlying structure, in order to confirm that it is really there. Without getting too philosophical about what 'reality' means here (admittedly, a deep discussion), we want to demonstrate the reality of the hyperfine structure, that it is not simply a quantum theorist's idea of what ought to be true. According to first order (quantum) perturbation theory, Estimate the frequencies using the results of first order perturbation, the perturbing hamiltonian is given by

$$H_{hf} = A(\mathbf{I} \cdot \mathbf{J}), \quad (1)$$

where \mathbf{I} is nuclear angular momentum, and \mathbf{J} the spin plus orbital angular momentum of the spectroscopic term. The natural eigenstates or eigenkets maybe be

labeled, $|FM_F\rangle$, where $\mathbf{F} = \mathbf{I} + \mathbf{J}$, which we met in the optical pumping experiment. The energy corresponding to each ket or state is a line on an energy diagram. We may suppose two such lines exist if we can observe a transition between them. Oh, sorry, that's backwards. We suppose two such lines exist when we observe a spectral line! How do we corroborate the real existence of the states? Let's leave this particular philosophy of physics question for a deeper truth. We want to remind ourselves how all physics, new physics in particular, becomes a trustable addition to 'knowledge' (whatever *that* is :).

A. References

1. *High Resolution Spectroscopy*, Ch.6, section 6.6 in our text.[1] Our experiment relates directly to the discussion of saturation absorption spectroscopy of Rubidium, however, the entire chapter lays the necessary physics background for the experiment, especially 6.3. The set up that I've implemented differs somewhat from everyone else's, (e.g. Melissino's set up is like many one can find in the 'literature', two papers of which will be useful for us; my set up is most like the one they use at caltech; I will include their 'manual' for reference as well)
2. Arthur Schawlow's nobel prize address[2] gives a good overview of 'subdoppler' spectroscopy, which is what we'll be doing, using the technique of saturation absorption spectroscopy. We'll be using a lockin amplifier in the way that he describes. The money-shot for our purposes is figure 2, however, from the point of view of his contribution to physics, that would be (in my opinion, just my opinion) figure 7. Subdoppler spectroscopy, made possible by the technique of saturation absorption spectroscopy, made deep comparisons between quantum theory and atomic (and molecular) physics possible. There was also a kind of curious artefact of the technique. Question: how to account for all those peaks? Do they all correspond to electric dipole transitions between (hyperfine-split) energy levels? Answer: no. There is something new here. It is called a 'cross over resonance'.
3. *Doppler-free saturated absorption: Laser spectroscopy*[3] a very good 'tutorial' paper published in the American Journal of Physics that describes the techniques referred to in the above

references, and which address ‘the curious artefact’ referenced above.

4. *About Lock-in Amplifiers*, Stanford Research Systems (SRS) technical applications note. There is an even more brief description of the technique in Melessinos[1], in section 3.8.
5. *Using Etalons*, a very simple, very brief discussion about Fabry-Perot etalons, composed as technical applications document for Melles Griot, Inc. We will use an etalon as an optical ruler for frequency changes of 300 MHz. And, of course, there is a discussion of the Fabry-Perot etalons in Melessinos[1], in section 4.6.

B. Procedure

We will do this experiment somewhat in reverse order. We will try to acquire the hyperfine structure first, using the technique of saturation absorption spectroscopy, first, and then we will obtain the simple absorption spectrum with saturation techniques, second.

1. Saturation absorption spectroscopy

We use a tunable diode laser to sweep the frequency of a beam of photons through an energy interval that can excite Rb I atoms from the ground state to one of the low lying excited states. Instead of an interference filter guaranteeing that only certain transitions are possible, the wavelength and ‘detuning’ range of the laser itself will guarantee which transitions (electric dipole!) are possible. The set-up for the first experiment is shown schematically in figure 1.

The frequency swept laser light is passed through a cell containing rubidium vapor and the transmitted light is detected using a PIN diode. The fond hope is to obtain a signal that looks like (for the one of the $^{85}\text{Rb}_{37}$ dips) like a dips with a series of notches in it, as shown in figures 6.25 and 6.26 in our text[?]. The number of notches depends on actual hyperfine structure of the terms participating in the electric dipole transitions.

The energy level structure of Rb is shown below. Experimentally, one sees two spectral lines for each isotope of Rb, transitions which are designated “a” and “b” on the energy level diagrams in figure IB 1.

Doppler broadening, however, obscures the far smaller hyperfine splitting of the excited state. To see the separate transitions from one hyperfine-split (ground) state to the

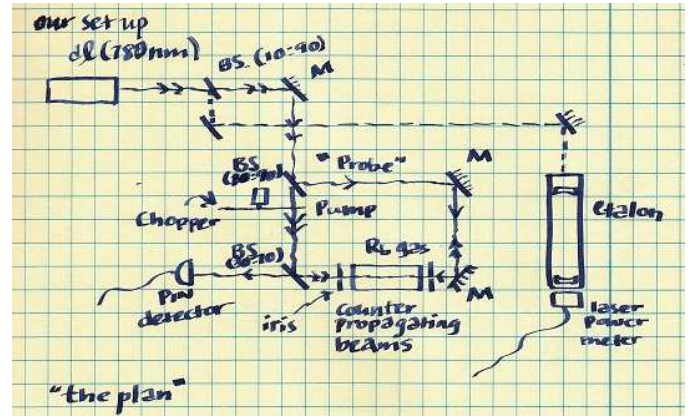


FIG. 1. Schematic for the Rb I absorption experiment. We use beam splitters and mirrors to try to demonstrate the saturation effect, that is, to make visible the separate transitions between one hyperfine state in the ground state and one hyperfine state in the excited state (of the sort $F \rightarrow F'$, where the prime indicates the excited state).

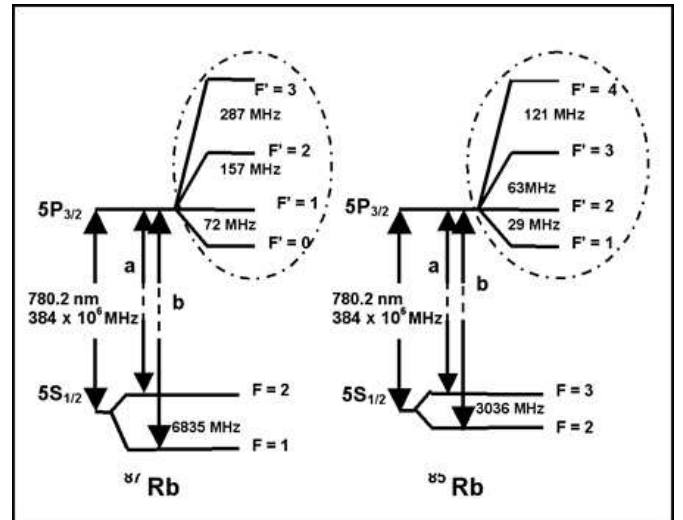


FIG. 2. Partial energy level diagram for Rb I, showing the split ground state $^2S_{1/2}$ and an excited state, $^2P_{3/2}$, for the two naturally occurring isotopes of Rb I.

excited hyperfine-split states, the ones ‘allowed’ by selection rules for electric dipole transitions, one must somehow get around the confounding nature of Doppler broadening. One technique which has proved to be very powerful in this regard is saturation absorption spectroscopy, described in the references above. We will need to add a second, far older technique, called phase sensitive detection, which typically involves the use of some means of signal modulation and the lock-in amplifier, as shown in figure IB 1. These are powerful and proven techniques in modern physics research.

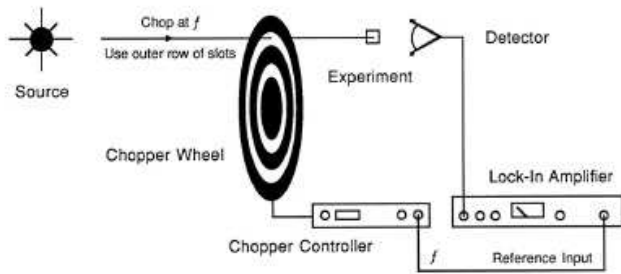


FIG. 3. In this application, a single optical beam is chopped by the outer row of slots, and the reference output from the right BNC is used to lock the lock-in amplifier to the chop frequency. This text is shamelessly lifted from SRS technical note on optical choppers

We will try the following: for both isotopes, obtain the so-called Doppler-free spectrum of one of the absorption dips, and account for *all of its features*, comparing theory with experiment. Question: are there more notches or lines than pairs of hyperfine transitions? Yes! What are the extra notches? (See the discussion of crossover frequencies in the Preston's article[3]). Be sure of quantum numbers of the transitions you are exciting. Be sure to record the best spectra from each isotope, obtain hardcopy and tape them into your lab notebook, along with the settings of all the instruments, so that you could in principle recreate the data (one *always* has to do this!). Save the data file, and write down the path name in your lab notebook.

2. Absorption spectrum of Rb I

This "simple" laser technique can resolve the ground-state hyperfine (hf) splitting of both isotopes which is possible since the laser linewidth is very small compared with the Doppler broadening of the spectral lines. Using the simple technique, schematically diagramed below in figure IB2 we can see four big blobby dips. Try to get a complete spectrum showing all four blobs at different intensities, say, one high, and one low. take the best spectrum and get hardcopy, and tape the figure into your lab notebook (along with all the settings). Compare theory and experiment. In this case, this means identifying the quantum numbers associated with each dip, and comparing the gaps with the known frequency intervals (a good reference is Rao[4]). Estimate, roughly, the temperature of the Rb atoms from the Doppler broadening of the lines. Is there any difference in the spectra as the intensity of the laser is changed? Can you account for the differences?

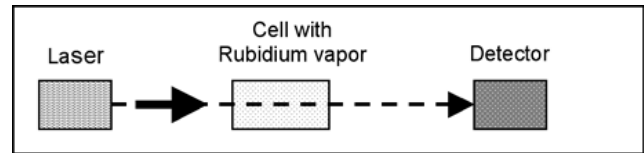


FIG. 4. Schematic (simple version) for the Rb I absorption experiment. We can simply reposition the PIN diode detector to block the probe beam (or the pump beam, for that matter) to collect the absorption spectrum without using Doppler-free techniques.

3. Questions to Ponder:

1. Have a look at figure 2. Draw for yourself an *absorption* spectrum commensurate with it that is both quantitatively and qualitatively correct. Take a shot, make some order of magnitude calculations, and commit yourself to an informed guess—make a sketch, label your axes, and be ready to defend your choices. How many lines (dips) do you expect to see, taking into consideration both isotopes?
2. How does the random thermal motion of the atoms in the gas cell affect the absorption spectrum? Why, without taking really drastic measures, would one see (if one had a really narrow line width laser, with a line width, say, or 1 MHz), just 4 blobby dips, and, since 'blobby dips', is a precise technical term, estimate what the width of the dips would be at half their depth (bear in mind that the 'spectrum' may just as easily be understood a function of frequency as of wavelength).
3. What is saturation-absorption spectroscopy? How does it work? And by 'work' I mean, precisely how are the separate transitions to the separate hyperfine states, in the excited state, from the separate hyperfine states in the ground state resolved?
4. What is a crossover resonance, and why do they occur, as Preston claims[3]
5. Taking the definition of resolving power R , to be the dimensionless ratio, $R = \lambda/\Delta\lambda$, what is the resolving power of the set up without crossing the probe and pump beams, and, without phase-sensitive detection? What is the resolving power, using the technique of saturation-absorption spectroscopy, and with phase-sensitive detection?
6. . What is the signal to noise ratio (speaking of 'resolving' the hyperfine structure of the transition)? What Try to estimate the extent to which the lock-in amplifier improves the signal to noise ratio. Express your result in $dB's$ (you will want to look up decibels).

7. What is phase-sensitive detection, and what is a lock-in amplifier?

8. What is an etalon, and how does it work? About how long should a cavity be if it is to have a 'free-spectral-range' of 300 MHz?

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- [1] A.C. Melissinos Jim Napolitano, *Experiments in Modern Physics*, 2nd. Ed.
 [2] The Nobel Prize in Physics 1981 was divided, one half jointly to Nicolaas Bloembergen and Arthur Leonard Schawlow "for their contribution to the development of laser spectroscopy" and the other half to Kai M. Siegbahn "for his contribution to the development of high-resolution

- electron spectroscopy".
 [3] D.W. Preston, *Doppler-free saturated absorption: Laser spectroscopy*, Am. J. Phys. **64**, 1432, (1996).
 [4] G. N. Rao, M. N. Reddy, and E. Hecht, *Atomic hyperfine structure studies using temperature/current tuning of diode lasers: An undergraduate experiment*, Am. J. Phys. **66**, (1998) which is also posted to our site.