Hyperfine Spectrum of Rubidium: laser spectroscopy experiments

Physics 480W
(Dated: Sp24, ver. 1.2)

I. RESEARCH QUESTIONS AND OBJECTIVES FOR THESE EXPERIMENTS

The technique of absorption spectroscopy is used to probe and detect the energy level structure of the ground state of Rubidium, Rb I, $^2S_{1/2}$, the spectroscopic term, which is known to be split by a tiny amount on account of magnetic interaction between the spins of the outermost electron, and that of the nucleus. In effect, the spectroscopy we do today tells us about nuclear properties and so combines atomic and nuclear physics.

1. How big is the effective magnetic field at the location of the nucleus created by the outer electron's magnetic moment? Compare the ground state splittings with theory, following Melissinos [1], section 6.3. Using this development (cf. especially equation 6.24), estimate $\langle B_e(0) \rangle$. Compare this expectation value of known magnetic fields to get some perspective for its magnitude. Is it big or small? What do you expect (before you begin)? Given our methodology, what is its uncertainty? Is the uncertainty sufficiently small to use the result for to make an estimate of the size of the anomaly (a_e) of the magnetic moment of the electron, typically quantified as,

$$a_e = \frac{g-2}{2}, \qquad (1)$$

where g is the electron's 'g-factor'.

2. measure the hyperfine splitting *for each isotope,* and compare with accepted values, with the following details in mind:

   (a) how large is the hyperfine splitting of the ground state, $^2S_{1/2}$ term, and what is an appropriate unit of measure? Do we need saturation-absorption techniques for this?

   (b) what are the hyperfine splittings of the excited state, $^2P_{3/2}$ term, that can be reached with a nominal wavelength of 780nm from the ground state? Here we need saturation-absorption techniques to perform sub-Doppler spectroscopy, certainly. Help the reader understand what is entailed in the technique, both experimentally and theoretically. You will need to explain what 'saturation' means. The saturation intensity is an important figure of merit. How might one use the measurements of the cross-over resonances to help determine (and modestly reduce) the uncertainty in the gap spacings (energy gaps)?

3. measure the FWHM (full width half max) of the blobs (also called dips) to estimate the temperature of the Rb atoms in the vapor; consider exhibiting the Gaussian fit and ask: should it be Gaussian, and should the full width at half max., (FWHM) be a little greater than, a little less than, or equal to the room temperature? Give physical arguments to support your work.

A. Procedures

1. 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 line width is very small compared with the Doppler broadening of the spectral lines. Using the simple technique, schematically diagrammed below in Fig. 1(a) we can see four big blobby dips (Fig. 1(b) But this is not what the actual set up looks like on our optics table in SCST292. That setup, Fig. 2, incorporates a rectangular optical cavity with counter propagating pump and probe beams (to be discussed presently) that permits a kind of sub-Doppler spectroscopy called saturation absorption spectroscopy (Background readings nos. 1-4 are essential reading). In any case, the simpler set up (Fig. 1(a)) may be realized by carefully insert a beam-block in the bottom leg of the optical cavity between the two mirrors. If everything is well aligned, one can readily capture the signal from the photodiode (and etalon) using the TOPAS Gui (Fig. 3)

In any case, with the simpler set up, try to get a complete spectrum showing all four blobs at different intensities, say, one high, and one low. Make sure you document everything that is done in your lab notebook. Sketch or tape in data set images. Make sure everyone knows where the data are kept and what is stored in each file (document this!). 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[2]). 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?
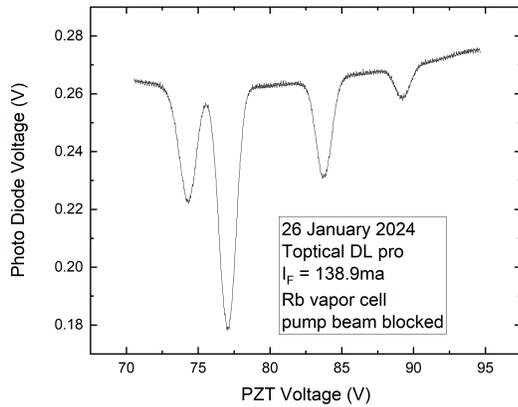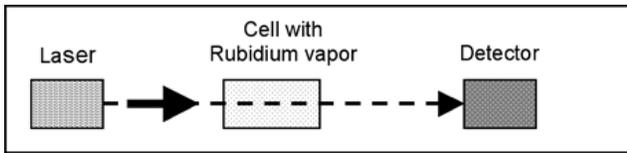
FIG. 1. (a) Schematic (simple version) for the Rb I absorption experiment. We can simply insert a beam block as described to collect the absorption spectrum without using Doppler-free techniques. (b) One sees for big absorption blobs as the piezo-electric transducer(pzt) voltage is scanned. The pzt voltage serves to tilt a grating that tunes the diode laser. Wow there is a lot of understanding packed into that simple sentence!
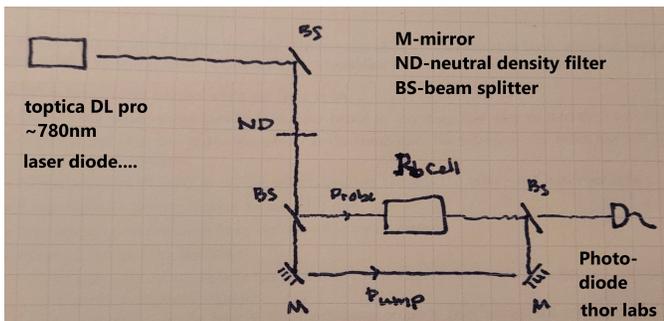
FIG. 2. Schematic for the Rb I absorption experiment. We use beam splitters and mirrors to create the so-called pump and probe beams that are used to eliminate Doppler-broadening of each transition, permitting us to observe the hyperfine structure of the ground state of the Rb-isotopes (87 and 85).

2. Saturation absorption spectroscopy

We use a tunable diode laser to sweep the frequency of a beam of photons though an energy interval that can excite Rb I atoms from the ground state to one of the low lying excited states. Please watch the Youtube video `https://www.youtube.com/watch?v=htjtNoqsY2Y` to get a really good idea of the *extended cavity diode laser*, although we use an even simpler version of this system.
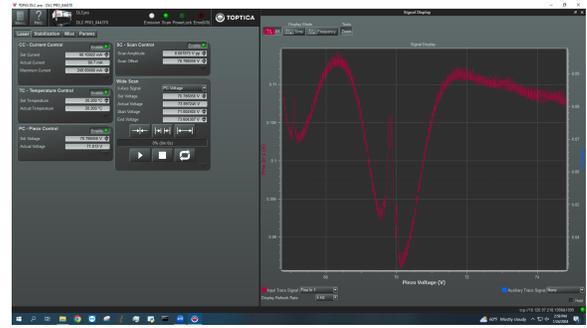
FIG. 3. Note, the screen shot shown here, captured by the TOPAS GUI, involves a scan of the pzt voltage wide enough to record only one of the four 'blobs' completely. Why are there four? What pzt voltage scan amplitude is needed to get all four blobs? Which are associated with $^{85}Rb_{37}$, and so on. If all goes swimmingly, we'll be able to obtain an absorption spectrum that with all four blobs. The etalon data will be needed to make the abscissa proportional to detuning frequency. The accepted value of the gap between the 2 outermost dips is 6.8347 GHz. A portion of the incident beam is deflected to an etalon using a beam splitter (70t,30r). The etalon provides frequency notches every 300 MHz.

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 to observe.

The frequency swept laser light (swept using piezoelectric transducer) 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 $^{85}Rb_{37}$ dips) like a dips with a series of notches in it, as shown in Fig.s 6.25 and 6.26 in our text[1]. 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 Fig. 4.

Doppler broadening, however, obscures the far smaller hyperfine splitting of the exited state. To see the separate transitions from one hyperfine-split (ground) state to the 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 Fig. 5. This is a powerful and proved techniques in modern physics research. This set up does not specify where
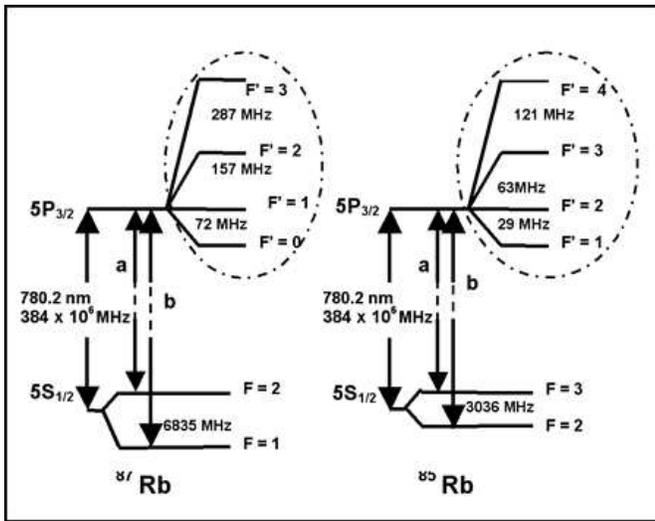
FIG. 4. Partial energy level diagram for Rb I, showing the split ground state $^2S_{1/2}$ and an excited state, $^2P_{3/2}$, for the two naturally occurring isotopes of Rb I.

the chopper might go, on the optics table. Sketch how we might realize it (the set up) for our optical cavity.
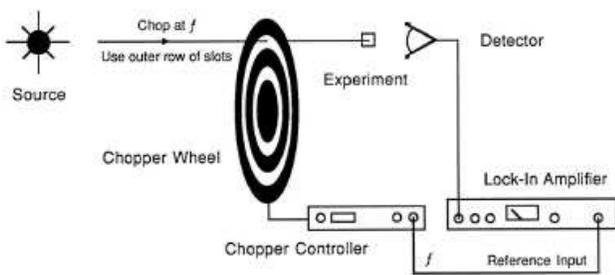
FIG. 5. In this application, a single optical beam is chopped by the outer row of slots, and the reference output from the right BNC is used to lock the lock-in amplifier to the chop frequency. This text is shamelessly lifted from SRS technical note on optical choppers

For both isotopes, obtain the so-called Doppler-free spectrum of all four of the absorption dips, and of each dip individually, and account for *all of its features*, comparing theory with experiment. Question: are we able to see now all of the features we expected the first time we obtained a saturation absorption spectrum? This is of course a 'loaded' question. Review again discussion of crossover frequencies in the Preston's article (Background reading #3). Be sure of quantum numbers of the transitions you are exciting. Be sure to record the best spectra from each isotope, each blob, etc. etc. obtain 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.

3. Test for 'saturation'

Which arrangement arrangement of ND filters (see legend in Fig. 2 for the definition of ND) interposed before or after the gas cell trapping the Rb atoms ('pre' or 'post') creates the deepest absorption dips? Meditate on Background reading #5. These two arrangements are shown schematically in Fig. 6 Please look at Fig. 1 again. Which arrangement leads to the deepest absorption dips? Why would there be any difference at all? This is the question to be addressed. The actual measurement that this question is meant to highlight of course is the measurement of the intensity of the input laser beam into the optical cavity (that part containing the gas cell in Fig. 2), which is to be compared with the saturation intensity of the transition.
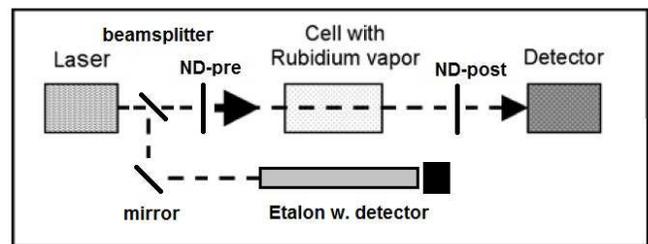
FIG. 6. A schematic for a test of saturation. See A neutral density filter (ND) can be placed before the beam enters the gas cell (ND-pre) or after the beam exits the gas cell (ND-post), allowing us to compare the absorption of laser beams of very different intensities within the gas cell which are nevertheless of the same intensity at the detector.

B. Background readings

1. *High Resolution Spectroscopy*, Ch.6, esp. 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. *Quantum Mechanics, A Paradigms Approach,* D.H. McIntyre, esp. Chapter 11 on *Hyperfine Structure*

and the Addition of Angular Moment. It will certainly help to review Section 12.2.2, Spin-orbit coupling for review (for all students who have recently read for PHYS 330 at USD, Quantum Mechanics).

3. Arthur Schawlow's Nobel prize address[3] gives a good overview of 'sub-Doppler' spectroscopy, which is what we'll be doing, using the technique of saturation absorption spectroscopy. We'll be using a lock-in amplifier in the way that he describes. The money-shot for our purposes is Fig. 2, however, from the point of view of his contribution to physics, that would be (in my opinion, just my opinion) Fig. 7. Sub-Doppler 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 artifact 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'.

4. *Doppler-free saturated absorption: Laser spectroscopy*[4] 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 artifact' referenced above.

5. *Nonlinear spectroscopy of rubidium: an undergraduate experiment,* V Jacques, B Hingant, A Allafort, M Pigeard and J F Roch, Eur. J. Phys. **30** 921 (2009). This paper reports the state of the art results for this experiment.

6. *Demonstrating optical saturation and velocity selection in rubidium vapor*, Razdan & Van Baak, Am. J. Phys. **67** 832 (1999).

7. *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.

8. *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. The Etalon we use is part of the Laser Spectrum Analyzer System of Coherent, Inc. And there is literature describing it on our public course website in the Laser Spectroscopy experiment readings. Note: the etalon is a 'confocal Fabry-Perot' etalon, and we will become familiar with it through use and worksheets.

II. AN HISTORICAL PERSPECTIVE ON LASER SPECTROSCOPY

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 (e.g., think MRI, even atomic clocks), was a remarkable quantum discovery. The substance of this discovery, so obvious with a simple tunable diode laser, goes back to Rabi's work[5] on the molecular beam method of measuring nuclear magnetic moments before WWII, to Pauli's recognition[6] that there should be such things in nature before that, and to Otto Stern's discovery of the spin of the proton.[7] 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 these physicists (Nicolaas Bloembergen) did both things,[3] and there is a line that runs from his work with nuclear resonance straight through Norman Ramsey's work, and Ed Purcell's work,[8] to Rabi's work. And Rabi learned the molecular beam method from Stern as his postdoc. Rabi's creative contribution was improving the detection technique with nuclear magnetic resonance. Later, Willis Lamb Jr. came into close connection with Rabi at Columbia, eventually using the beam-resonance technique to measure the energy level shift between the $^2S_{1/2}$ and $^2P_{1/2}$ terms of hydrogen's $n = 2$ eigenstates. This was one of the principal experiments that demonstrated the need to go beyond Dirac's synthesis of relativity and quantum mechanics, and one the touchstones of reality that 'grounded' the nascent[9] science of QED. Lamb's work[10] was a seminal work (Noble prize-Physics 1955), as was everything else discussed above. The story of scientific discovery has a great deal to do with innovation in technique and technology.

One of the common questions is this: 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 bandwith 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, $^2S_{1/2} \longrightarrow {}^2P_{3/2}$, 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, the perturbing Hamiltonian is given by

$$H_{hf} = A(\mathbf{I} \cdot \mathbf{J}), \qquad (2)$$

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 the 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 backward. 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 proven addition to 'knowledge' (whatever *that* is :).

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[1] A.C. Melissinos Jim Napolitano, *Experiments in Modern Physics*, 2nd. Ed.

[2] 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).

[3] 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".

[4] D.W. Preston, *Doppler-free saturated absorption: Laser spectroscopy*, Am. J. Phys. **64**, 1432, (1996).

[5] NobelPrize-Physics 1944. No Nobel lecture was given for obvious reasons. The seminal citation is a brief note in the physical review, just two columns of one page (how cool is that). I.I. Rabi, J.R. Zacharias, S. Millman, P. Kusch Phys Rev., 53 318, (1938). How many of his students were Noble Prize winners!? Why were they so honored? How did it happen?

[6] A. Pais, "Inward Bound, of matter and forces in the physical world", (OUP, NY 1986), see especially p. 315. Pauli's solution to the 'nuclear energy crisis', a missing particle which he predicted to exist, much like the prediction of the Higgs (by Higgs and others), was eventually called the neutrino (although he calls it the neutron, itself not yet discovered). I bring it up because Pauli is the first to recognize (predict) that the constituents of the nucleus may have *spin*.

[7] I. ESTERMANN, O. C. SIMPSON, AND O. STERN, 'The Magnetic Moment of the Proton', PHYSICAL REVIEW, 52, 535 (1937); this was the first notice of the result in US journals. See Stern's Nobel Prize address at www.nobelprize.org, Physics-1943.

[8] see the Nobel Prize addresses of Ramsey, Purcell, Bloembergen, and for all the other physics prizes at www.nobelprize.org

[9] A. Pais, *Op. cit.* See p.447ff. Pais was a young theorist who actually joined Feynman, Bethe, and Schwinger, and Rabi, et al., at the Shelter Island conference in 1947. Lamb presented his work there and Rabi reported Nafe's work on the hyperfine structure of the ground state of hydrogen.

[10] W. E. Lamb, Jr. and R. C. Retherford, Phys Rev., 72 (1947) 241; 79 (1950) 549; 81 (1951) 222. W. E. Lamb, Jr., Phys. Rev., 85 (1952) 259. W. E. Lamb, Jr. and R. C. Retherford, Phys. Rev., 86 (1952) 1014.