

APPARATUS AND DEMONSTRATION NOTES

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Frank L. H. Wolfs, *Editor*

Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627

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An undergraduate measurement of radiative broadening in atomic vapor

A. J. Hachtel, J. D. Kleykamp, D. G. Kane, M. D. Marshall, B. W. Worth, J. T. Barkeloo, J. C. B. Kangara, J. C. Camenisch, M. C. Gillette, and S. Bali^{a)}
Department of Physics, Miami University, Oxford, Ohio 45056-1866

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We show that one may quantitatively investigate radiative broadening of atomic transitions in the undergraduate laboratory using a traditional saturated absorption spectroscopy setup. © 2012 American Association of Physics Teachers.

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I. INTRODUCTION

Optical spectroscopy of atomic fine structure and the Zeeman effect form an indispensable component of the modern undergraduate laboratory curriculum.¹ With the growing popularity of home-built tunable diode laser systems,² a demonstration of the hyperfine structure of alkali atoms using saturated absorption spectroscopy (SAS) (Ref. 3) is becoming an important experiment in many undergraduate optics laboratories.⁴⁻⁶ A natural extension of SAS, which has not been traditionally emphasized, is to adjust the power of the pump beam and study the dependence of the hyperfine spectral linewidth on intensity. The purpose of this short note is to point out that one may use the SAS setup for an instructive investigation of radiative broadening, also known as power broadening, in room temperature atomic vapor.

Radiative broadening is an important fundamental phenomenon in light-matter interaction, attractive to students at many levels. Freshmen and sophomores are intrigued by the concept that the act of observing a spectral absorption line in an optical measurement broadens the linewidth. More advanced students are fascinated by the idea that even after various line-broadening mechanisms, such as Doppler broadening and pressure broadening, are suppressed, there still remain radiative broadening effects that prevent the observation of a spectral line with its “natural” linewidth, despite using low light-levels for the measurements. Radiative broadening of the spectral absorption profile occurs because the on-resonance absorption in the center of the profile is saturated at much lower intensities than the off-resonant wings.⁷ Therefore, as intensity rises, absorption in the wings rises faster than absorption in the center, leading to

a broadening of the profile. Radiative broadening occurs even at very low light intensities.

The experiment described in this paper is part of the advanced optics laboratory at Miami University, which is offered every year. The laboratory is focused alternately on either “optics and laser physics” or “atomic and molecular spectroscopy.”⁸ The SAS setup is built by the students in the advanced optics and laser physics laboratory as an assignment. This assignment includes the construction of the frequency-narrowed, tunable external cavity diode lasers.^{2,4,9} Sophomore students visit the advanced optics laboratory to see a demonstration of SAS.

II. BASIC SAS SETUP

Figure 1 shows the basic setup for SAS, comprising of three frequency-scanning laser beams (one strong and two weak), propagating through a sample of atomic vapor. In our

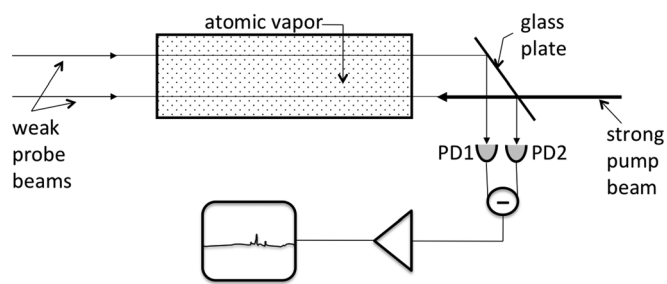


Fig. 1. Basic schematic for SAS. The outputs from photodiodes PD1 and PD2 are subtracted from each other, amplified, and displayed on an oscilloscope.

setup, we used room-temperature Rubidium vapor (72% ^{85}Rb and 28% ^{87}Rb). The goal of SAS is to study the Doppler-free hyperfine structure of Rb with linewidths approaching the natural linewidths. One of the two weak probe beams overlaps with the strong pump beam, which propagates in the opposite direction. The atoms moving perpendicular to these overlapped beams are simultaneously in resonance with both the strong and the weak beams, owing to the absence of any Doppler shifts. Specifically for these atoms, their absorption is saturated by the strong beam, which means that the weak probe passes through without being absorbed. This results in Doppler-free “holes” being “burnt” into the Doppler profile at the site of the hyperfine transitions.¹⁰

Doppler-broadened absorption peaks are shown in Fig. 2(a) for a weak frequency-scanned laser beam propagating through the Rb vapor. Shown is the output from PD1 when the strong pump beam is not allowed to enter the vapor cell. When the strong pump beam is allowed to enter the vapor cell, Doppler-free “hole-burning” is observed in the absorption spectra detected by PD2, as shown in Fig. 2(b). Figure 2(c) shows the intensity difference between PD1 and PD2. This figure shows that the Doppler-free hyperfine spectral features in ^{85}Rb and ^{87}Rb that were previously obscured by

Doppler broadening are revealed by SAS. The laser intensity used is less than the saturation intensity which is defined as the intensity at which the probability of a Rb atom being found in the excited state is 1/4. The saturation intensity for ^{85}Rb is 1.64 mW/cm^2 .⁷ A laser frequency scan across the $F_g = 2 \leftrightarrow F_e = 3, 2, 1$ transitions of ^{87}Rb is shown in Fig. 2(d). Figure 2(e) shows the results of a frequency scan across the $F_g = 3 \leftrightarrow F_e = 4, 3, 2$ transitions of ^{85}Rb . Each of these three hyperfine transitions is individually marked in Figs. 2(d) and 2(e). As is well-known, a characteristic of SAS is that we observe, in addition to the three hyperfine transitions, three “crossover” absorption peaks of similar width, but larger amplitude, located exactly midway between each pair of hyperfine transitions.¹⁰

The detection and amplification circuits and the optics employed in our setup closely follow the specifications described in an earlier work.⁴ Constructing the SAS setup shown in Fig. 1 and obtaining the spectra displayed in Fig. 2 are assignments for the seniors and Masters’-level students in the advanced optics laboratory. The sophomore students who visit the optics laboratory are given handouts of the observed spectra in Fig. 2 and are asked to measure the Doppler linewidths, followed by a linewidth measurement of the SAS hyperfine spectra. The frequency calibration for the

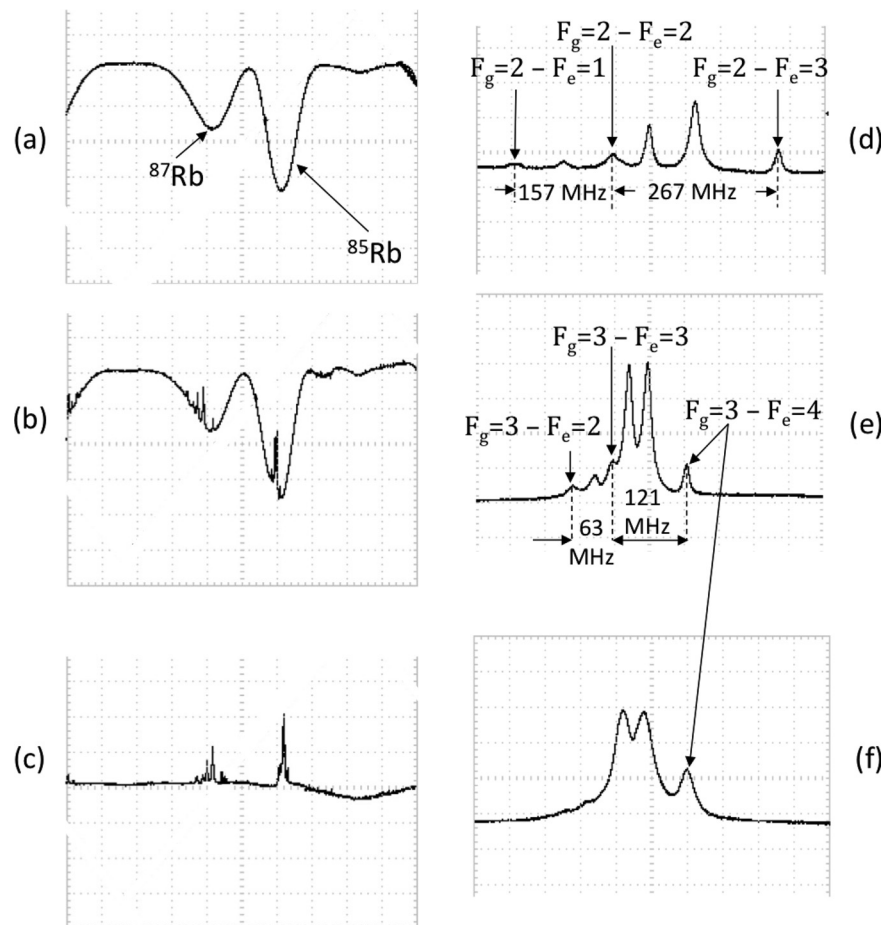


Fig. 2. Snapshots of oscilloscope traces displaying the intensity detected by photodiodes PD1, and PD2 on the y-axes as a function of the “laser frequency” on the x-axes: (a) Doppler broadened absorption spectra for ^{87}Rb (left) and ^{85}Rb (right) detected by PD1 when the strong pump beam is absent. (b) When the strong pump beam is present, “hole-burning” is observed in the absorption spectra detected by PD2. (c) The net absorption spectrum obtained by subtracting the output of PD1 (a) from PD2 (b). Reducing the frequency scan and zooming in on the Doppler-free spectral features in (c) reveals hyperfine spectra for ^{87}Rb and ^{85}Rb , shown in (d) and (e), respectively, for a laser intensity of 6.87 mW/cm^2 . The linewidths are measured to be 14.0 MHz , close to the predicted value of 13.6 MHz . (f) Same as (e), except with a higher laser intensity of 46 mW/cm^2 . This spectrum shows the power broadening of the ^{85}Rb hyperfine spectrum. The vertical scale is $10\times$ the scale in (e). Note: The horizontal scales for (a)–(c) are $10\times$ those for (d)–(f).

x-axis of the traces shown in Fig. 2 is provided by the known frequency-splittings between the hyperfine lines, as indicated in Figs. 2(d) and 2(e). Using this calibration, the students are asked to go back to Fig. 2(a) and measure the Doppler linewidth. They find that the results are in good agreement with predictions obtained with the theoretical expression¹¹ for the Doppler linewidth $\gamma_{\text{dopp}} = 2\nu_0 \sqrt{2k_B T \ln 2 / mc^2}$, where ν_0 is the resonance frequency, which is equal to c/λ_0 , m is the atomic mass, and T is the temperature.

III. DEMONSTRATION AND MEASUREMENT OF RADIATIVE BROADENING

The six Doppler-free SAS linewidths in Fig. 2(d) or 2(e) are identical but are not equal to the natural linewidth of 5.98 MHz. The students find that the measured linewidth is a few times larger than the natural linewidth. At this point, the students are introduced to the concept of “power broadening” or “radiative broadening,” i.e., line-broadening of the atomic energy levels caused by the presence of the light. This broadening exists even for the rather weak intensities employed in SAS.

The sophomores are given a qualitative demonstration of power broadening by turning up the illumination, well above the saturation intensity. The students see how the spectrum shown in Fig. 2(e), taken at an intensity of 7.5 mW/cm², transforms into the spectrum shown in Fig. 2(f), taken at an intensity of 50 mW/cm². None of the individual hyperfine transitions are discernable in Fig. 2(f), except for the $F_g = 3 \leftrightarrow F_e = 4$ transition in ⁸⁵Rb.

The students in the advanced optics laboratory, who built the SAS setup, are taught in lecture the well-known theory for radiative broadening^{7,11} and are shown the derivation of the power broadened linewidth γ_{rad}

$$\gamma_{\text{rad}} = \gamma \sqrt{1 + I/I_{\text{sat}}}, \quad (1)$$

where γ is the natural linewidth, I is the intensity of the light illuminating the atom, and I_{sat} is the saturation intensity. The students measure the “full width at half maximum” (FWHM) for any one of the six peaks seen in the saturated absorption hyperfine spectrum in either Fig. 2(d) or 2(e) as a function of the laser intensity. For the spectra shown in Figs. 2(d) and 2(e), obtained at an intensity of 6.87 mW/cm², the measured linewidths are 14.0 MHz, which is close to the theoretical value of 13.6 MHz, predicted using Eq. (1). It turns out that it is easier to use one of the larger crossover peaks for this measurement. The measured line widths as function of the laser intensity are shown in Fig. 3. The curve in Fig. 3 shows the theoretical prediction made using Eq. (1).

The FWHM measurement can be performed directly with the oscilloscope, provided the following two precautions are taken. First, the oscilloscope input impedance (typically 1 M Ω on most oscilloscopes) must be matched to that of the BNC cable (typically 50 Ω) from the detector-amplifier circuit. We used a 50 Ω inline terminator between the cable and the oscilloscope. This prevents broadening of the spectral features due to an impedance mismatch. Second, at low intensities, the signal strength becomes weak and electronic noise begins to dominate, causing fluctuations in the spectrum. One must avoid the temptation to make measurements on a spectrum that has been averaged over several scans because the average waveform is broadened by the noise,

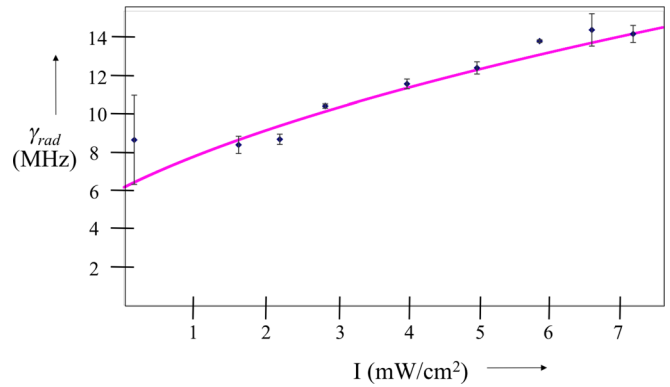


Fig. 3. The radiative broadened linewidth γ_{rad} as a function of intensity. The intensity seen by the atoms is the sum of the strong pump beam and the counter-propagating weak beam. The curve shows the theoretical prediction made using Eq. (1).

even though it may appear cleaner. At each intensity, we found that it is best to make a FWHM measurement using the data obtained in a single scan and repeat this process several times. At the lowest intensities, we found it necessary to average two or three scans in order to be able to make a reliable FWHM measurement. Three FWHM measurements were taken at each intensity. Each data point in Fig. 3 represents the average of these three measurements and the error bar represents their standard deviation divided by \sqrt{N} where $N=3$ in our case. This approximate and simple method works reasonably well for the range of intensities shown in Fig. 3. At high intensities, the errors are dominated by uncertainties in determining the baseline, while measuring the FWHM for the hyperfine peaks in Fig. 2(e). If time permits, one may choose to model the hyperfine spectrum as the sum of six Lorentzian peaks. This procedure would automatically take into account the effect of slight increases of the baseline of each Lorentzian due to small contributions from neighboring peaks. For the range of intensities shown in Fig. 3, these errors are small and we chose to ignore them in the interest of having the students finish the lab in a timely manner.

IV. CONCLUSION

Radiative broadening of atomic spectral lines is a well-known result which, to the best of our knowledge, has traditionally not been emphasized in the undergraduate laboratory, especially at the low intensities shown in Fig. 3. We have shown that SAS may be used for a quantitative investigation of radiative broadening of atomic hyperfine structure. This experiment naturally caps off the students’ journey in light-matter interaction and spectroscopy, from fine structure and D_1 – D_2 lines in an alkali vapor, to hyperfine structure and SAS.

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^{a)}Electronic mail: balis@muohio.edu

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Tangent Galvanometer

The tangent galvanometer, invented in 1837, is still in use: I recently visited an institution where it was being used to measure the horizontal component of the magnetic field of the earth. This example in the Greenslade Collection was made by J. H. Bunnell of New York. The company, still in existence, was founded in 1878 by Jessie Bunnell, a pioneering Civil War telegraphist, and originally specialized in making telegraph instruments. Later, the company branched out and made test instruments that were used by telegraphers and other electricians of the era. This is a top-of-the-line model, with multiple coils to give a wide range of current sensitivities. (Notes and photograph by Thomas B. Greenslade, Jr., Kenyon College)