

# Direct optical measurement of sodium hyperfine structure using a cw dye laser and an atomic beam\*

F. Schuda, M. Hercher, and C.R. Stroud, Jr.

*Institute of Optics, University of Rochester, Rochester, New York 14627*

(Received 2 January 1973)

A cw dye laser is described which allows short-term frequency stability of 10–15 MHz. An experiment using this laser to measure the hyperfine absorption spectrum of the sodium  $D_2$  line is described. Results from this experiment are presented showing a resolution of the  $F=2 \rightarrow 3$  and the  $F=2 \rightarrow 2$  transitions.

Recent development of cw dye lasers has given promise of providing a new tool for really high-resolution optical spectroscopy. The efforts to realize this promise have been frustrated by the difficulty of obtaining a sufficiently stable single-mode laser which is also continuously tunable without jumping (mode hopping) so as not to miss the very narrow hyperfine components of a spectral line.

The laser described below overcomes these difficulties to a large extent, as is evidenced by the resolution obtained in the absorption spectrum, Fig. 3.

The dye laser, shown in Fig. 1, is similar to that described by Pike and Hercher.<sup>1</sup> Pumping radiation from an argon ion laser is focused by lens  $L_1$  through the high-reflectance dye laser mirror  $M_1$  and into the dye cell. The dye laser emission from this point in the dye cell is focused by lens  $L_2$  onto the dye laser output mirror,  $M_2$ , almost 1 m away. As shown, the dye laser cavity contains three Brewster-angle dispersing prisms and a stage supporting a number of etalons. The relatively long dye laser cavity is used primarily to reduce the sensitivity of an axial mode frequency to changes in the optical length of the cavity. A small change  $\Delta L$  in the length of the cavity (due to refractive-index variations in the flowing dye, mechanical vibration, etc.) causes a change in the resonant frequency of the cavity given by

$$\Delta\nu = (\nu/L)\Delta L,$$

where  $L$  is the length of the cavity and  $\nu$  is the resonant frequency. We found that by increasing the cavity length from 20 to approximately 100 cm, we improved the short-term (30 sec) single-axial-mode frequency stability from 50 MHz to between 10 and 15 MHz. Moreover, the use of a long cavity allowed us to image the dye cell onto the plane output mirror (rather than collimating the dye laser beam with lens  $L_2$ ) without sacrificing the ability to operate in a single axial mode; this cavity configuration is highly stable and served to reduce intensity fluctuations in the dye laser output. Pumped by a 2-W (all lines) argon ion laser, this dye laser had an output of about 100 mW, although it was operated in the vicinity of 5–10 mW for the experiments described here.

Single-mode operation of the dye laser was obtained through the use of three uncoated tilted glass etalons of varying thickness, but all having the same refractive index. These etalons were placed on a single stage which

could be rotated about a vertical axis, thereby synchronously tuning all three etalons.<sup>2</sup> The etalons could be tuned relative to one another by rotation about their horizontal axes. With these etalons alone, fine tuning of the dye laser—brought about by rotation of the stage about its vertical axis—would cause the dye laser output to jump from one axial mode to the next in steps of approximately 150 MHz. In order to smoothly scan the frequency of the dye laser without these jumps, we added a Brewster-angle etalon of the proper thickness to the stage. As the stage was rotated, this etalon produced a change in the optical length of the resonator which, over a range of a few GHz, caused the axial-mode frequency to smoothly change in synchronism with the pass band of the tilted etalons. This technique proved adequate for smoothly scanning the dye laser frequency across the various components of the sodium lines in an atomic beam of sodium.

In order to maintain good frequency stability of the single-mode dye laser, it was necessary to (i) provide a moderate degree of vibration isolation for the entire laser system (we used a steel table mounted on inner tubes), and (ii) enclose the dye laser cavity to reduce air currents and acoustic pickup. By observing these precautions we could maintain better than 20-MHz frequency stability over 1-min intervals, and better than 5-MHz stability over 0.5-sec intervals.

Figure 2 illustrates the experimental setup for scanning the  $D_2$  hyperfine absorption spectrum of atomic sodium. Before performing the experiment the dye laser had to be coarse tuned to the sodium line. This was accomplished by using a standard sodium discharge lamp as a

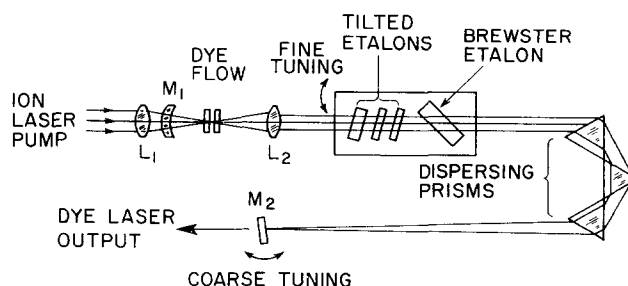


FIG. 1. Single-mode cw dye laser with provision for smooth tuning. The over-all cavity length is approximately 1 m.

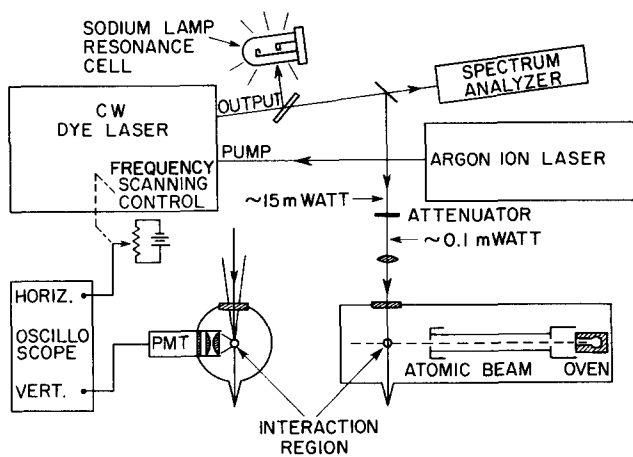


FIG. 2. Experimental apparatus for the measurement of light scattered from an atomic beam of sodium as a function of optical frequency.

resonance cell. The lamp was heated to about 220 °C and then turned off. While the bulb was still hot, the laser was tuned to resonance and etalons were inserted consecutively in the laser and individually tuned to resonance until single-mode operation was achieved. The mode structure was monitored by a piezoelectric scanning spectrum analyzer with a free spectral range of 1500 MHz. When the laser was operating single mode and at a frequency near the center of the Doppler-broadened  $D_2$  line, the laser light was totally scattered within 1 mm upon entering the sodium bulb. The laser was then within a few GHz of the hyperfine lines and was ready to be focused down and adjusted to intersect the sodium atomic beam at right angles ( $\pm 0.005$  rad).

The atomic beam apparatus was of standard design with circular apertures.<sup>3</sup> An electrically heated oven at approximately 350 °C produced a particle beam with a collimation of approximately 0.002 rad. The particle flux was calculated to be about  $10^{10}$  atoms/sec with a velocity of  $5 \times 10^4$  cm/sec.

The interaction region where the atomic and laser beams cross was less than 1 mm in diameter. The resonance radiation scattered from this region was collected by an  $f/1$  lens system and relayed to a photomultiplier at one of the side ports of the vacuum chamber. Although we have only measured the intensity of the scattered light to date, light could be easily recorded by a spectrum analyzer if the emission spectrum was desired, since the scattered light intensity was quite high.

In order to obtain the absorption spectrum shown in Fig. 3, the laser was tuned through about 400 MHz while the scattered intensity was monitored. This was accomplished by linking up the scanning control on the laser to a voltage divider which fed the horizontal input of an oscilloscope. The output of the photomultiplier drove the vertical deflection of the oscilloscope, and the result was a plot of scattered intensity versus laser frequency.

Figure 3 shows two components of the  $D_2$  line, the  $F=2-3$  and the  $F=2-2$  transitions. These lines are separated by about 60 MHz. Another hyperfine compo-

nent,  $F=2-1$ , is not well resolved since it is only about 35 MHz from the  $F=2-2$  transition. The hyperfine lines have a calculated natural width of 20 MHz. From the observed linewidths of 30–35 MHz, we infer that the instrumental width is about 15 MHz. This width is due mainly to the laser beam not being accurately perpendicular to the atomic beam. The spectrum was measured with the linearly polarized incoming laser beam intensity greatly attenuated by a linear polarizer. At higher intensities it is difficult to resolve the  $F=2-2$  transition from the  $F=2-3$  transition because of the effects of optical pumping; when the laser is tuned to the  $F=2-3$  transition, all of the excited atoms return to the  $F=2$  ground level and can absorb over and over again. On the other hand, when the laser is tuned to the  $F=2-2$  transition, the excited atoms can decay to either the  $F=2$  or  $F=1$  ground level. This causes a gradual depletion of the population of the  $F=2$  ground level and an accompanying reduction in the amount of light absorbed at the  $F=2-2$  transition frequency.

The experimental results of Fig. 3 are preliminary in the sense that they do not represent the ultimate resolution obtainable with this system. Neither do they present a complete story of the sodium  $D$  lines.<sup>4</sup> We have, however, established the feasibility of a relatively simple method for the direct optical measurement of hyperfine structure in absorption lines. Among the advantages of this technique are (a) it offers resolution better than that obtained previously by any purely optical method with instrumentation which, even including the atomic beam, is no more complicated than that used for saturation spectroscopy.<sup>5</sup> (b) It provides a method for making detailed measurements of line shapes which can easily and unambiguously be compared with theory.

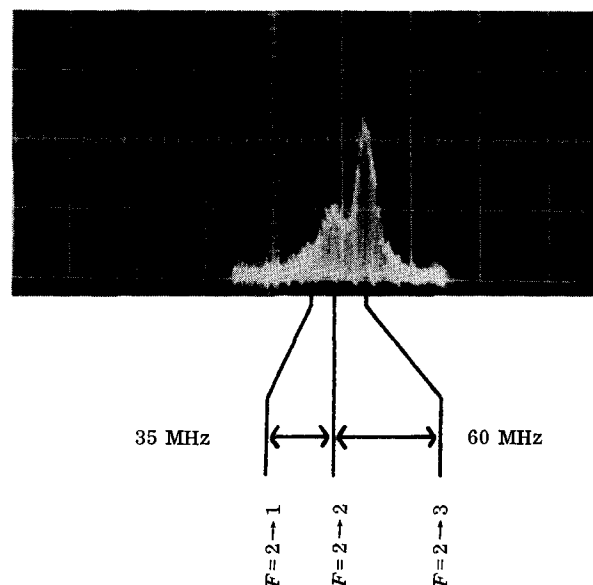


FIG. 3. Light scattered from an atomic beam of sodium as a function of the optical frequency of the incident radiation. Shown here are three hyperfine components (one of which is barely resolved) of the  $D_2$  absorption line. (The dye laser emission was chopped during the scan to provide a zero level.)

(Such a technique is attractive for use in fundamental experiments to test the foundations of radiation theory.<sup>6</sup>) (c) It allows easy measurement of the emission line shape as a function of detuning and applied field strength. Moreover, because of the high spectral radiance of the cw dye laser, spectra can be obtained over a range of several hundred MHz in few msec or less.

---

\*Work supported in part by the Advanced Research Projects Agency under Contract No. DAHCO 4-71-C-0046.

<sup>1</sup>H. A. Pike and M. Hercher, *Opt. Commun.* **3**, 347 (1971).

<sup>2</sup>M. Hercher, *Appl. Opt.* **8**, 1103 (1969).

<sup>3</sup>N. F. Ramsey, *Molecular Beams* (Clarendon, Oxford, England, 1956).

<sup>4</sup>M. Baumann, W. Hartmann, H. Kruger, and A. Oed, *Z. Phys.* **194**, 270 (1966); M. L. Perl, I. I. Rabi, and B. Senitzky, *Phys. Rev.* **98**, 611 (1955); D. A. Jackson and H. Kuhn, *Proc. R. Soc. A* **167**, 205 (1938).

<sup>5</sup>T. W. Hansch, I. S. Shahin, and A. L. Schawlow, *Phys. Rev. Lett.* **27**, 707 (1971).

<sup>6</sup>As examples of such experiments, see H. M. Gibbs, *Phys. Rev. Lett.* **29**, 459 (1972), and J. M. Wossner, D. K. Anderson, and R. T. Robiscoe, *Phys. Rev. Lett.* **29**, 1126 (1972).