

- ¹B. J. Hunt, *The Maxwellians* (Cornell U.P., Ithaca, 1991). This work argues that Maxwell himself favored the potentials, but later developments led to a preference for the fields.
- ²Y. Aharonov and D. Bohm, "Significance of Electromagnetic Potentials in the Quantum Theory," *Phys. Rev.* **115**, 485–491 (1959).
- ³H. Boersch, H. Hamisch, D. Wohlleben, and K. Grohmann, "Antiparallele Weißsche Bereiche als Biprisma für Elektroneninterferenzen," *Z. Physik* **159**, 397–404 (1960).
- ⁴R. G. Chambers, "Shift of an Electron Interference Pattern by Enclosed Magnetic Flux," *Phys. Rev. Lett.* **5**, 3–5 (1960).
- ⁵F. G. Werner and D. R. Brill, "Significance of Electromagnetic Potentials in the Quantum Theory in the Interpretation of Electron Interferometer Fringe Observations," *Phys. Rev. Lett.* **4**, 344–347 (1960).
- ⁶V. Chandrasekhar, M. J. Rooks, S. Wind, and D. E. Prober, "Observation of Aharonov–Bohm Electron Interference Effects with Periods h/e and $h/2e$ in Individual Micron-Size Normal-Metal Rings," *Phys. Rev. Lett.* **55**, 1610–1613 (1985).
- ⁷G. Timp, A. M. Chang, J. E. Cunningham, T. Y. Chang, P. Mankiewich, R. Behringer, and R. E. Howard, "Observation of the Aharonov–Bohm Effect for $\omega_c \tau > 1$," *Phys. Rev. Lett.* **58**, 2814–2817 (1987).
- ⁸In an experiment, of course, one measures differences in potential. Once a reference potential ϕ_0 is specified (commonly $\phi_0=0$), ϕ itself may be considered measurable. Likewise, one usually measures $\nabla \times \mathbf{A}$, but once a gauge is specified \mathbf{A} may be considered measurable (in that gauge).
- ⁹R. C. Gelinis, U.S. Patents #4 429 280; 4 429 288; 4 432 098; and 4 447 779 (1984).
- ¹⁰B. Lee, E. Yin, T. K. Gustafson, and R. Chiao, "Analysis of Aharonov–Bohm effect due to time-dependent vector potentials," *Phys. Rev. A* **45**, 4319–4325 (1992).
- ¹¹Reference 9 purports to measure \mathbf{A} directly, in the Coulomb gauge. It makes use of the fact that while gauge invariance remains a good symmetry, the superconducting state itself is not gauge invariant. Its gauge is taken to be $\nabla \cdot \mathbf{A} = 0$, in which the London equation holds, and so nothing in principle then prevents \mathbf{A} itself from being measured. In the Josephson junction, the measurable phase depends on $\int_1^2 ds \cdot \mathbf{A}$ [or simply on $\mathbf{A}(\mathbf{r})$ since an external \mathbf{A} may be considered constant through the thin junction]. It is a separate question whether one is really measuring \mathbf{A} in a fixed gauge or simply measuring $\int dt \mathbf{E}$ (when $\phi=0$). This is the same as the question of whether one really measures the potential ϕ or simply the field via $\int ds \cdot \mathbf{E}$. We do not enter into these interesting discussions; our purpose here is only to motivate interest in \mathbf{A} . Regarding the question of gauge and Josephson junctions, see P. W. Anderson, "Special Effects in Superconductivity," in *Lectures on the Manybody Problem*, Ravello, 1963, edited by E. R. Caianiello, Vol. 2 (Academic, New York, 1964), pp. 113–135; and J. Frohlich and U. Studer, "Gauge Invariance and Current Algebra in Nonrelativistic Manybody Theory," *Rev. Mod. Phys.* **65**, 733–802 (July 1993).
- ¹²Reference 10 provides a measure of $\oint \mathbf{A} \cdot ds$ by the conventional Aharonov–Bohm effect.
- ¹³W. R. Smythe, *Static and Dynamic Electricity* (Hemisphere, New York, 1989), 3rd ed., revised printing. Section 7.10, p. 291.
- ¹⁴C. E. Baum, "Vector and Scalar Potentials Away from Sources, and Gauge Invariance in Quantum Electrodynamics," Phillips Laboratory Physics Notes, Note 3 (10 October 1991).
- ¹⁵R. P. Feynman, R. B. Leighton, and M. Sands, *The Feynman Lectures on Physics* (Addison-Wesley, Reading, MA, 1964), Vol. II, Sections 15.4–15.5.
- ¹⁶E. J. Konopinski, "What the Electromagnetic Vector Potential Describes," *Am. J. Phys.* **46**, 499–502 (1978).
- ¹⁷J. D. Jackson, *Classical Electrodynamics*, 2nd ed. (Wiley, New York, 1975).
- ¹⁸Any vector \mathbf{V} has its own vector and scalar potentials, for $\mathbf{V} = \mathbf{V}_T + \mathbf{V}_L$, where
- $$\mathbf{V}_T = \frac{1}{4\pi} \nabla \times \int d^3r' \frac{\nabla' \times \mathbf{V}(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|}, \quad \mathbf{V}_L = -\frac{1}{4\pi} \nabla \int d^3r' \frac{\nabla' \cdot \mathbf{V}(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|}$$
- \mathbf{V}_T and \mathbf{V}_L may each be nonlocal even if \mathbf{V} is local.
- ¹⁹J. A. Stratton, *Electromagnetic Theory* (McGraw-Hill, New York, 1941).

Teaching physics with 670 nm diode lasers—construction of stabilized lasers and lithium cells

K. G. Libbrecht, R. A. Boyd, P. A. Willems, T. L. Gustavson,^a and D. K. Kim^b
Norman Bridge Laboratory of Physics, California Institute of Technology 12-33, Pasadena, California 91125

(Received 23 September 1994; accepted 22 February 1995)

We describe the construction and operation of stabilized 670 nm diode lasers for use in undergraduate teaching labs. Because they emit low-power visible radiation, 670 nm lasers are safe and aesthetically pleasing, and thus are an attractive alternative to near-infrared diode lasers in the undergraduate laboratory. We also describe the fabrication of a robust and reliable lithium atomic vapor cell, which can be used with the 670 nm diode lasers to perform a variety of atomic physics experiments. © 1995 American Association of Physics Teachers.

I. INTRODUCTION

As inexpensive sources of narrowband tunable coherent light, semiconductor diode lasers are becoming important research tools with widespread applications in modern academic and industrial laboratories. Because of their relatively low cost (compared to other tunable laser sources) they are also well-suited for incorporation into undergraduate teaching labs. By scanning the laser emission over atomic or molecular resonance lines, a variety of interesting and fundamental physics experiments can be performed.

A recent paper by MacAdam *et al.*¹ describes several techniques for constructing and operating stabilized diode lasers for the undergraduate laboratory. These lasers operate in the near infrared, at 780 or 852 nm, and can be tuned to scan over various rubidium or cesium resonance lines, respectively. Unfortunately, radiation at these wavelengths is almost completely invisible to the human eye, which creates several problems when incorporating near-IR lasers into undergraduate labs. A primary concern is safety, since even a milliwatt of laser radiation can cause irreparable eye damage.

${}^7\text{Li}$ (92.5%, $I=3/2$, $\tau=27.2$ nsec.)

${}^6\text{Li}$ (7.5%, $I=1$, $\tau=27.2$ nsec.)

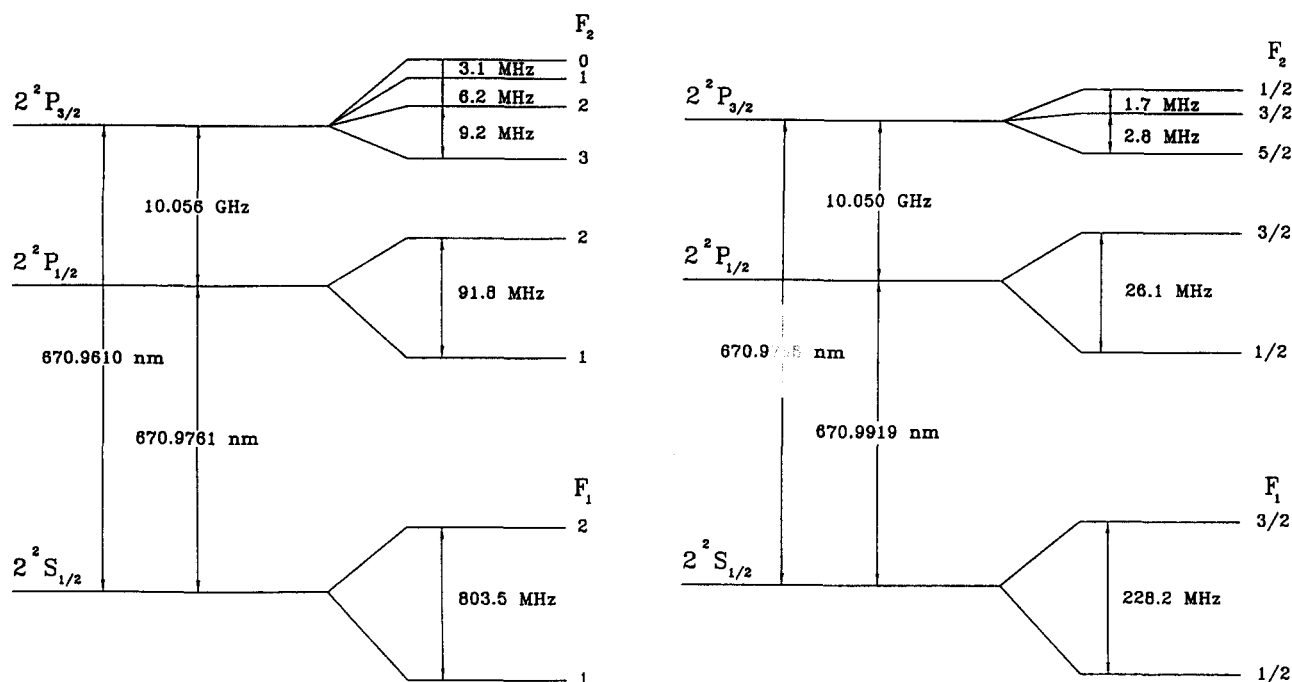


Fig. 1. Energy level diagrams (Ref. 27) for the lower S and P levels of ${}^7\text{Li}$ and ${}^6\text{Li}$. The natural abundances, nuclear spins, and excited state lifetimes are given for each isotope, as well as the fine-structure and hyperfine-structure splittings. Note the close spacing of the $P_{1/2}$ and $P_{3/2}$ excited states, and the small isotope shift, allowing both $S \rightarrow P$ transitions and both isotopes to be spectroscopically observed with a single diode laser.

This problem is especially serious with invisible lasers, since one can inadvertently stare into a beam without knowing it. Thus students should wear protective goggles in the lab, and in addition some amount of infrared viewing equipment is needed for the lab experiments.

An alternative to near-infrared lasers is to use visible diode lasers, particularly at 670 nm where they can be tuned over the lowest $S \rightarrow P$ resonance lines of lithium (see Fig. 1). This alternative is an attractive one for a number of reasons, including: (1) the lasers emit low-power visible radiation, and are thus as eye-safe as helium–neon lasers; (2) no IR viewers, IR cards, or TV imaging equipment is necessary for most experiments; (3) the experiments are more aesthetically pleasing, which is important for a teaching laboratory; (4) both lithium D -lines, $2S_{1/2} \rightarrow 2P_{1/2}$ and $2S_{1/2} \rightarrow 2P_{3/2}$, can be excited by a single laser; (5) both stable lithium isotopes, ${}^7\text{Li}$ and ${}^6\text{Li}$, can be spectroscopically observed; (6) the ground-state hyperfine splitting is small (803 and 228 MHz for ${}^7\text{Li}$ and ${}^6\text{Li}$, respectively) in comparison with most other alkali atoms, and thus accessible with less expensive signal generators.

On the negative side, 670 nm diode laser systems, including the one described here, are at present more difficult to use than near-infrared diodes, and lithium must be heated to higher temperatures than other alkali metals, of order 400 °C, to produce an atomic vapor with an appreciable optical depth. While turn-key diode laser systems are available at 670 nm and near-IR wavelengths,^{2,3} the current cost of a single unit, of order \$12 000, is quite high for most undergraduate laboratories, particularly when several lasers are desirable for doing a range of experiments. Lithium and other alkali vapor cells are now commercially available as well.³

In this paper, we present the design and construction of 670 nm diode lasers and lithium vapor cells suitable for use in undergraduate laboratories. These are used in a new senior-level undergraduate lab course at Caltech, which consists of a series of experiments in atomic and optical physics. Our experience indicates that undergraduate students can successfully conduct satisfying and significant lab experiments with the equipment described herein. In addition to presenting the design and construction details for both our diode lasers and lithium cells, we also describe a step-by-step procedure for aligning and tuning the lasers to the lithium resonance lines.

II. DIODE LASER PREPARATION

A commercially available 670 nm diode laser typically needs to have its protective can removed, and the diode's front facet antireflection (AR) coated, in order to consistently control the laser output using optical feedback techniques.⁴ This is not necessary with many near-IR diodes,^{1,5} which can be used very successfully with no further preparation. Although we achieved limited success with uncoated 670 nm diodes, we found that their performance was not reliable enough for everyday use in an undergraduate laboratory.

Since we did not have a general-purpose coating apparatus available, we built a small special-purpose vacuum chamber for this task, which is shown in Fig. 2. We obtained good results using Toshiba TOLD 9215 diodes (purchased in small quantities from Thor Labs⁶), and we continue to use these exclusively in our undergraduate lab. Other types of 670 nm diodes work as well,⁴ and our choice might not be the best one. Further experimentation may yield better performance

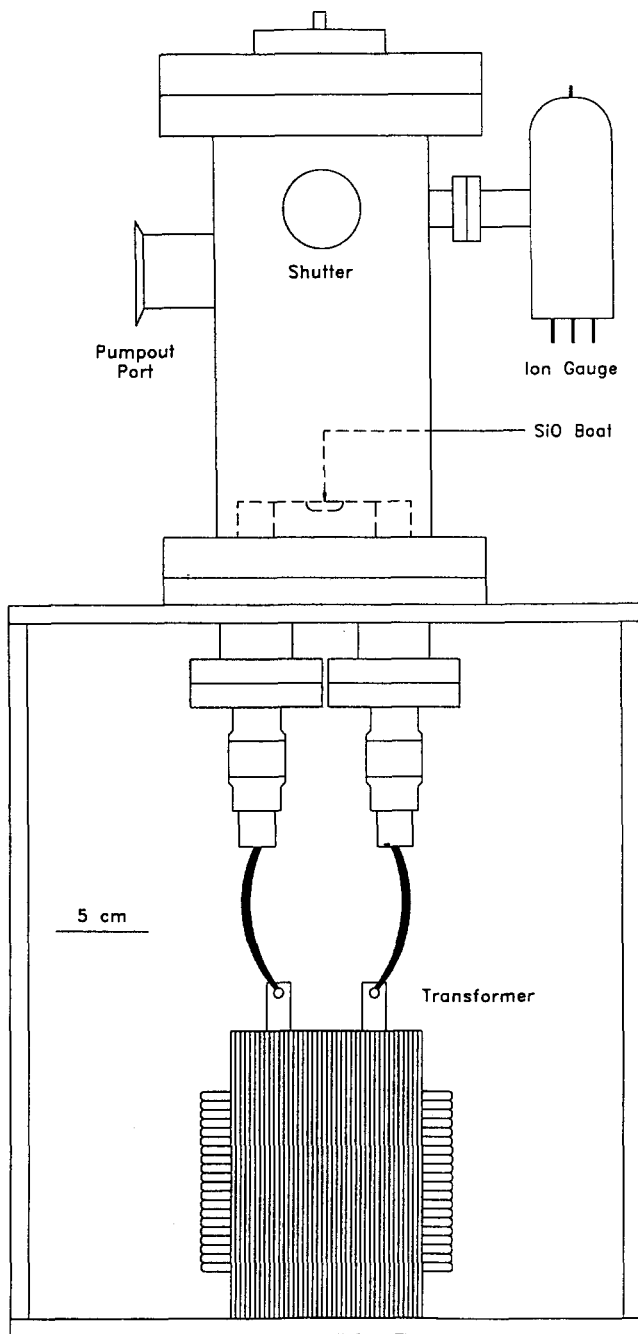


Fig. 2. Vacuum apparatus used to evaporate SiO antireflection coatings onto the front facets of 670 nm diode lasers. A SiO boat is clamped between two high-current feedthroughs, and is driven using a high-current step-down transformer powered by a standard 110 V 15 A variable transformer (not shown). A portable turbomolecular pump connects to the pumpout port, and a rotary motion feedthrough is used for a shutter to block the SiO beam. Diodes are attached one at a time to the top flange of the vacuum chamber.

(better tunability, stability, ease of use, etc.) with other commercially available diodes. Higher-power 670 nm lasers, which are now becoming available, are especially promising in this regard.

The procedure we follow to AR coat the diodes' front facets is essentially that described recently by Boshier *et al.*⁴ As described in that paper, we found that the application of a suitable AR coating is made considerably simpler by the fact

that one can use the diode's own laser output to monitor the coating process. Thus a crystal thickness monitor is not needed.

A special SiO boat⁷ is used, mounted between two high-current feedthroughs, and is heated by passing about 250 A through it. This current is supplied by a standard 110 V 15 A variable transformer,⁸ stepped down by a large transformer⁹ to provide the high current at low voltage needed by the boat. The total price of the vacuum system and coating hardware was of order \$2500, not including the vacuum pump.

With this relatively small vacuum chamber we initially had problems with the red-hot SiO boat heating the diode laser when the shutter was open, thus changing the diode's threshold current and interfering with our ability to monitor the AR coating process.⁴ This problem was corrected by mounting the diode laser in a heat sink attached to the top of the vacuum chamber, exposing only the central part of the diode mount to the boat, and by adding a radiation shield between the SiO boat and the diode.

The chamber is evacuated by a portable 60 ℓ /s turbomolecular pump,¹⁰ which achieves a base pressure in the chamber below 2×10^{-7} Torr. After baking out the chamber and the SiO boat, the boat is heated to its operating temperature with the beam shutter open, and the coating is deposited on the front facet of the diode. The coating process itself takes only a few minutes, during which time the chamber pressure rises to typically $\sim 10^{-6}$ Torr, and sometimes as high as $\sim 10^{-5}$ Torr. Experience indicates that this pressure increase is not detrimental to the final AR coating. As with Boshier *et al.*, we monitor the diode's threshold current as it is being coated, using the laser's internal photodiode, and we stop the coating when the threshold is near its maximum value. With a bit of experience we now achieve yield rates of usable AR-coated diodes of nearly 100%. However, some coated lasers are more easily tuned to the lithium resonance lines than others, probably owing to the diode's internal mode structure before coating.

III. DIODE LASER MOUNTING HARDWARE AND ELECTRONICS

Once a 670 nm diode laser is AR coated, it is mounted in a temperature-controlled housing incorporating an optical feedback system to line narrow and tune the laser output frequency. Unlike Boshier *et al.*, we are able to obtain satisfactory results using only a simple Littrow grating feedback system, similar to that commonly used with near-IR lasers^{1,11} (see Fig. 3). We achieve best results with the feedback grating mounted as close as practical to the diode laser, in order to maximize the spacing between adjacent external cavity modes (see below). By running without a separate etalon between laser and grating,⁴ we eliminate one optical element and adjustment from the apparatus. The Littrow configuration is also simpler than the Littman-Metcalf configuration¹² used in the commercial 670 nm diode lasers available from New Focus,² although the latter gives better performance and a larger tuning range. The reason for our success with Littrow grating feedback is not clear, but it may be that an AR coating on a TOLD 9215 laser is only partially effective, and thus the diode's internal cavity provides some wavelength selection in addition to that provided by the grating. It should be noted that with Littrow feedback the temperature and current stability requirements are fairly stringent, and the laser does not have a large continuous tuning range. However, we

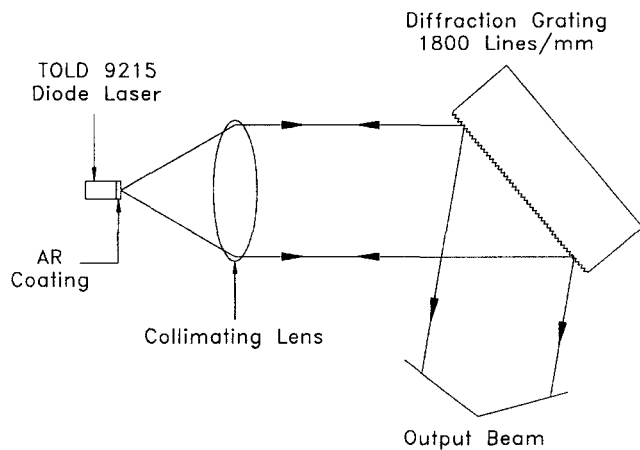


Fig. 3. Optical feedback to a diode laser using a diffraction grating in a Littrow configuration.

have found that it is possible to achieve good temperature and current stability with homemade controllers. Further, we typically scan the laser only over the lithium *D* lines, and thus do not need a large continuous tuning range.

The essential features of our diode laser mounting system are shown in Fig. 4. The laser itself is mounted in an aluminum block (which is easily adapted to different diode case styles), and is temperature-controlled using a sense resistor in the block and a thermoelectric cooler (TEC).¹³ The block and TEC are surrounded and held in place by a lucite cover, bolted to an aluminum base. The temperature servo circuit was derived from that described by Bradley *et al.*¹⁴ With only a single stage of temperature regulation, we measured diode temperature drifts of ~ 2 mK per degree change in room temperature. This resulted from weak temperature gradients in the aluminum block along with the finite distance between the laser and sense resistor, as determined by a heat-flow model. To reduce this problem and provide better optical feedback stability, we also temperature control the diode base plate with a pair of TECs and an independent servo circuit. To ensure good performance the servo bridges and preamplifiers are mounted inside the laser box, and components with small temperature coefficients are used in critical locations.¹⁴ With this system, the diode temperature drifts are reduced to ≤ 1 mK/h.

We use the diode current controller described by Libbrecht and Hall,¹⁵ which gives excellent long-term stability as well as low current noise. Both the temperature and current controllers are homemade and fairly easy to build with some electronics experience, yet they perform as well as expensive commercial diode controllers. Although the total system described here is not difficult to construct, the ultralow noise and high stability it provides are probably more than are necessary for most applications. Nevertheless, we have found it both convenient and satisfying when our lasers remain on resonance for many hours at a time, especially when several are in use at once in the undergraduate laboratory.

The external grating is glued to a home-made grating mount (also shown in Fig. 4). We chose a homemade mount rather than a commercial one (although the latter are inexpensive and available in many styles) for reasons of both stability and flexibility. A typical diffraction grating is fairly large and heavy, and thus not easily mounted with sufficient

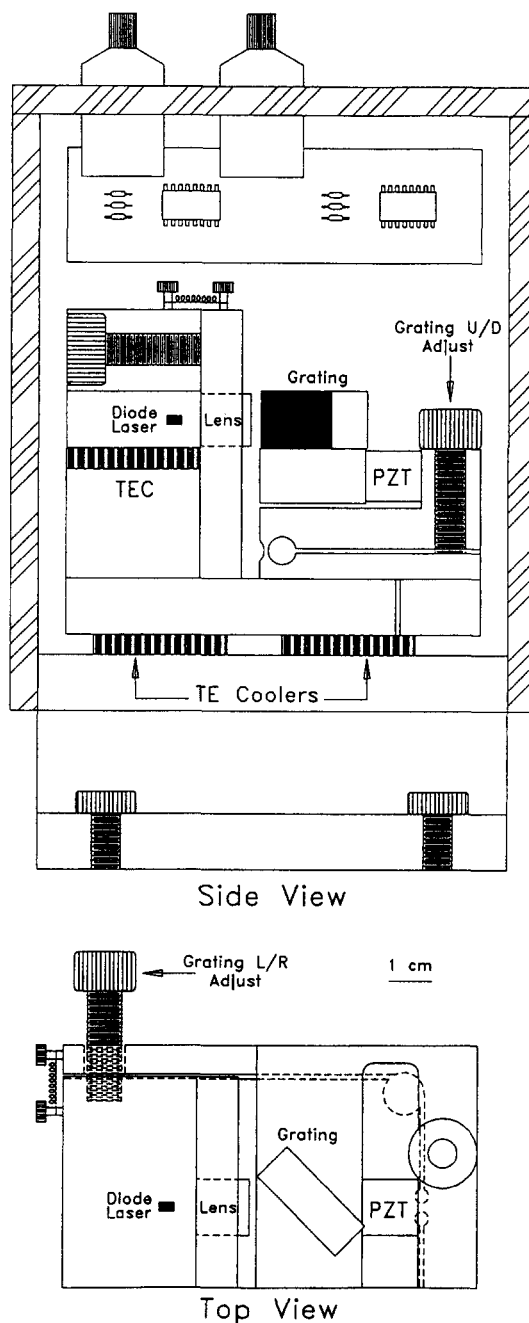


Fig. 4. Diode laser housing, showing two layers of temperature stabilization and optical feedback from a diffraction grating. Holes in the Lucite cover for the exiting laser beam and various electrical feedthroughs into the box are not shown. Two additional small holes provide access to adjustment screws for the laser collimating lens and grating angle.

stability in small commercial mounts, especially when fine control with a piezoelectric translator (PZT) is required. The compact mount shown in Fig. 4 easily accepts a variety of gratings, without the need to cut them down to a smaller size, and with flexure hinges it is quite stable (particularly when attached to a thermally controlled base plate, as in Fig. 4). The PZT is a simple tube¹⁶ glued into the mount and driven with a homemade high-voltage controller.¹⁷ One undesirable feature of this grating mount is that it has fairly low mechanical resonance frequencies, typically ~ 1 kHz, so modulation of the laser frequency by moving the grating position

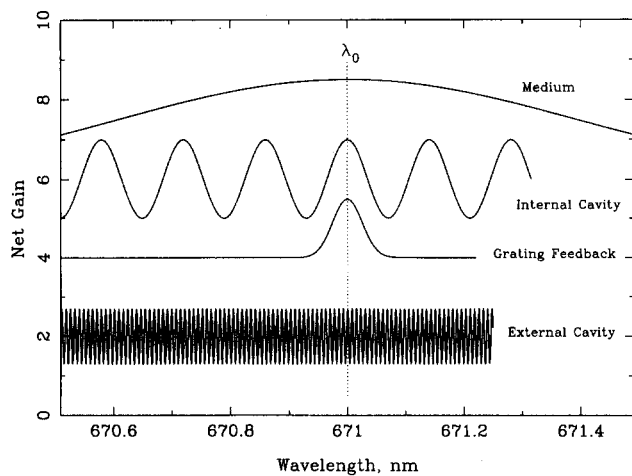


Fig. 5. Schematic representation for the various components of diode laser gain, as described in the text.

with the PZT can only be done slowly. In practice we have not found this to be much of a problem, and the laser can readily be scanned or frequency locked by varying the PZT voltage. For demanding applications, faster laser response can be obtained by modulating the diode injection current.

Finally, the entire diode laser assembly is covered with a Lucite box, which has three small holes for adjustment wrenches, a hole for the exiting laser beam, and a number of electrical connections. We have had much experience with this laser mounting system, after trying others, and find it has several desirable features. The mount is compact and robust, yet it is easy to assemble and disassemble and can be readily adapted to other diode lasers and gratings.

IV. DIODE LASER SETUP AND ALIGNMENT

The details of how optical feedback from diffraction gratings serves to line narrow and stabilize diode lasers are beyond the scope of this paper (see Ref. 11 and references therein). And while an in-depth knowledge of diode laser physics is not required to use these devices with good results, some understanding is useful when aligning and tuning the laser. In this section, we describe a procedure that makes it straightforward for undergraduate students (as well as teaching assistants) to become proficient at quickly tuning lasers to the lithium resonant lines.

A diode laser will tend to lase at the mode frequency with the greatest net gain (i.e., stimulated emission minus optical losses).¹⁸ Once the laser begins to lase in this mode, stimulated emission limits the number of electron-hole pairs which are available for lasing in other modes, and the result is a laser with a single-mode (i.e., single frequency) output beam. (Note this does not always happen ... a diode laser will often lase in two or more modes at the same time, and sometimes the output frequency will vary rapidly and chaotically over a broad frequency range. While these behavior patterns are interesting and the subject of some research, we typically try to find a place in parameter space where the laser operates in a single mode.) The goal of the laser alignment is to obtain stable operation at a predetermined frequency, which we will assume is at one of the 671 nm lithium resonance lines. Considering the various contributions to the laser gain profile shown in Fig. 5, we have the

Output Wavelength of typical TOLD 9215 Diode Laser

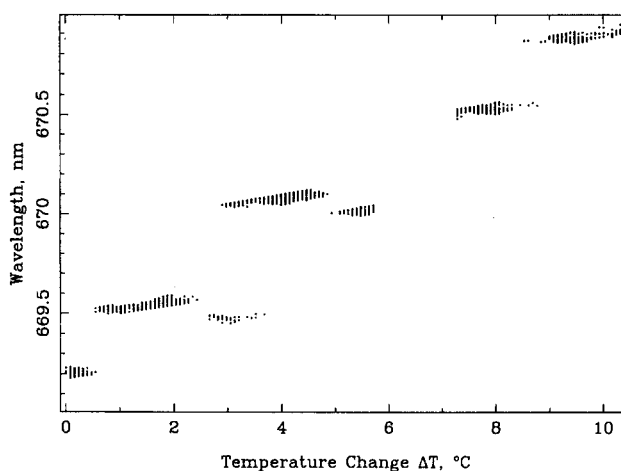


Fig. 6. Output wavelength of a typical free-running Toshiba TOLD9215 diode laser, as a function of diode temperature. The vertically displaced dots represent different diode output powers, from a minimum of ~ 1 mW (shorter wavelengths) to a maximum of ~ 6 mW (longer wavelengths). Note at some temperatures the laser did not operate single mode, while at some temperatures the laser would operate stably in two different modes.

following.

- (1) The laser medium—This depends on the properties of the semiconductor material from which the laser is made, in particular the band gap. The gain from this contribution shows a broad peak, whose position depends mainly on laser temperature. In practice, we set the laser temperature using the temperature controller so that it operates near 671 nm. Once this is done, the medium gain curve is so broad that it is unimportant for determining the precise wavelength of the laser.
- (2) The internal cavity—The diode junction forms a small etalon, which continues to affect the gain curve even after the application of a monolayer AR coating. This translates to an effective frequency dependent net gain function with free spectral range $FSR \approx 93$ GHz ($\Delta\lambda \approx 0.14$ nm) for our lasers. The cavity gain function shifts in frequency with changes in the diode temperature and current; roughly 30 MHz/mK at fixed current and 3 MHz/ μ A at fixed temperature. Figure 6 shows the measured wavelength of a typical free-running uncoated TOLD 9215 laser as a function of temperature, for various injection currents. As the temperature is increased, the peaks of both the medium gain and the internal cavity gain curves shift to longer wavelengths. However, they do not shift at the same rate, and the result is that the laser “mode hops” to different peaks of the cavity gain function.¹¹ For this reason a typical uncoated diode laser without feedback cannot be tuned to any arbitrary wavelength.
- (3) The grating feedback—We use a visible holographic grating with 1800 lines/mm purchased from Edmund Scientific Co.,¹⁹ which gives about 20% retroreflection back to the diode laser. Assuming the diffraction limit of the grating, the spectral width $\Delta\nu$ of the grating feedback in first order will be given approximately by $\nu/\Delta\nu = N$, where ν is frequency and N is the number of grating lines subtended by the laser beam. With a 0.5 cm laser

beam width, $N=9000$ and $\Delta\nu\approx 50$ GHz. The position of this peak is determined by the grating azimuthal (L/R) angle.

- (4) The external cavity—We obtain the best results by pushing the grating up as close to the laser as is practical, giving an external cavity free spectral range of $\text{FSR}\approx 5$ GHz. This curve shifts by moving the grating position, which we do with the PZT in the grating mount. Note that one tunes through one FSR by moving the grating one wavelength. Also note that the grating rotates about a pivot point as it translates, which shifts the grating's gain function so its peak partially follows the external cavity peak. This increases the laser's tuning range,²⁰ but also results in the output beam shifting in angle as the laser frequency changes. We have not found the latter to be a serious problem, however, since we normally only wish to tune the laser across the lithium resonance lines, which results in only slight beam deflection.

Laser alignment procedure. In order to force the laser into single-mode operation at a predetermined frequency ν_0 , the gain from each of the components should peak at ν_0 as shown in Fig. 5. This is accomplished with the following procedure, which needs to be repeated occasionally to maintain proper alignment.

Setting the laser temperature—The laser temperature is set so that with 5 mW of output laser power (the operating power of the laser), the medium gain curve (see Fig. 5) is peaked around 670.96 nm, near the lithium resonance lines. This is done before the feedback grating is installed, or afterwards using a pick-off mirror between the laser and grating. The set temperature is only determined roughly at this point, since the medium gain is not very important for determining the laser wavelength.

Aligning the feedback grating—In order for the feedback grating to have the desired effect, it must accurately retroreflect the laser output beam. For this to happen the laser beam must be precisely collimated (by the collimating lens), and the grating up/down (U/D) angle must be precisely set to retroreflect the beam. In addition, the laser performs best when the grating left/right (L/R) angle is set so that peaks of the grating feedback and internal cavity gain curves coincide (see Fig. 5). Three adjustment screws located in and on the laser box are used for adjusting the collimating lens position and two grating angles.

To coarsely align the grating and attach it to its mount, one first turns the laser power up to a few milliwatts, carefully collimates the output beam, and places the grating on top of its mount so that the first order reflection from the grating nearly retroreflects back into the laser. One then manually tilts the grating back and forth to find the position of exact retroreflection, at which point the output beam intensity increases dramatically, which is observed as a bright flash. The initial attempts to place the grating are best done in a darkened room, since spurious faint reflections off the laser are useful for finding the position of exact retroreflection. One then glues the grating down in this retroreflecting position, with the adjustments to the grating mount in the center of their ranges. Aluminum foil shims work well for positioning the grating to the desired position, using a small lead weight to hold the grating down while gluing with 5 min epoxy. If necessary, the grating can be easily removed with a sharp tap.

When the glue dries, one optimizes the grating adjustments by minimizing the laser threshold current I_{thresh} ,

which is measured by applying a current ramp to the laser and observing the output power with a photodiode. Note the laser's threshold transition is much sharper with grating feedback than it would be with the laser free running. It should also be noted that I_{thresh} moves up and down periodically as L/R is adjusted; this happens as the grating feedback peak coincides with the different peaks in the internal cavity gain profile in Fig. 5. The L/R angle is set so that I_{thresh} is at one of these local minima (any one), and is later moved to pick the proper laser operating frequency.

Measuring the laser frequency—With the above procedure the laser is aligned for optimal feedback from the grating (with the collimating lens and grating U/D adjust), plus the peaks of the internal cavity and grating feedback gain curves are set to coincide (using the grating L/R adjust). Thus the laser is optimally aligned for lasing at some random (to be determined) wavelength. The next step is to make it lase at 670.96 nm, at the lithium resonance lines.

In order to tune to the resonance lines one needs a means to measure the laser's absolute wavelength to an accuracy of at least ± 0.02 nm. We achieve this with a scanning Michelson interferometer, specifically the Wavemeter-jr manufactured by Burleigh.²¹ A grating monochromator may also be used to measure the wavelength of the laser, if one is available with sufficient absolute accuracy. We found some care must be exercised using the Burleigh Wavemeter-jr, as optical feedback from the wavemeter input can adversely affect wavelength measurements. Best results were obtained by placing the Wavemeter-jr several meters from the laser, and observing the monitor output of the Wavemeter-jr with an oscilloscope. By adjusting the laser current and beam alignment into the Wavemeter-jr it is usually possible to achieve both single-mode operation of the laser and a reliable wavelength measurement.

With the ability to accurately measure the laser wavelength, the following steps are used to bring the laser to 670.96 nm.

- (1) Set the grating PZT voltage to 200 V (the middle of its range).
- (2) Align the collimating lens and both the grating angles to minimize I_{thresh} , as described earlier.
- (3) With an output power of a few milliwatts, direct the laser beam into the wavemeter, and adjust the beam alignment and laser current to get a stable wavelength reading. Record I_{set} , T_{set} (the laser current and temperature set points) and the output wavelength λ .
- (4) If the laser wavelength is more than 0.14 nm from 670.96 nm, go to step (2) and adjust the grating L/R angle to a new local minimum. If the grating L/R screw is turned *in* by one internal cavity FSR, the laser wavelength should *decrease* by about 0.14 nm. Go to step (3).
- (5) If the laser is less than 0.14 nm from 670.96 nm, adjust T_{set} by at most about half a degree, wait for the temperature to stabilize (a few minutes with our circuit and laser mount) and start over again at step (2).

It has been our experience that the 670 nm lasers described here must be realigned more frequently and more carefully than near-IR lasers. The latter are quite stable for weeks or even months, and once the laser is aligned to the atomic resonance, one need only turn the laser on and adjust the injection current to find the resonance again. Our 670 nm lasers, in contrast, usually need to be realigned to the lithium resonance lines before every lab session, even if they are in a

thermally stable environment and have been turned off for only a few days. Although the procedure appears somewhat laborious, with a small amount of practice most undergraduate students can realign a laser in about half an hour.

V. LITHIUM ATOMIC VAPOR CELL

It is more difficult to make an atomic vapor cell for lithium than for other alkali metals because of its low vapor pressure at room temperature. In order to achieve an optical depth near unity in the resonance lines, a reasonable-size lithium gas cell must be heated to nearly 400 °C, considerably hotter than for other alkali metals.

We examined several different solutions to the problem of producing a convenient lithium vapor cell to use in conjunction with our 670 nm diode lasers. One possibility is a simple vapor cell, consisting of essentially a stainless steel tube about 30 cm long with ultrahigh-vacuum (UHV) flanges welded to the ends, attached to two sapphire windows.²² The ends of the cell are heated slightly hotter than the body, to keep lithium from depositing on the windows. Sapphire windows are expensive, but they can withstand the high temperatures required and exposure to highly-reactive hot lithium vapor for long periods of time.²³ A UHV valve or copper pinch-off tube is also attached to the body of the tube for its initial pumpdown.

To assemble such a cell, we first thoroughly clean the vacuum components, then prepare and insert about five grams of lithium metal into the cell before sealing it and evacuating it with a turbo pump. We use ~3-mm-diam lithium wire to load the cells, which typically comes packed in mineral oil. Preparation of the metal is done in a nitrogen atmosphere,²⁴ and consists of cleaning the wire in acetone and scraping off the oxide layer with a knife. Lithium is soft and slow to oxidize in air, and thus relatively easy to handle in a glove box.

While evacuating the cell and gradually it for the first time, we found it very useful to monitor the lithium density using a laser tuned to one of the lithium resonance lines. (An alternative is to watch very carefully for lithium plating the windows.) The cell must be heated as much as 50 °C above the operating temperature before any lithium vapor appears, probably to allow the lithium to break out of a thin oxide layer which develops during assembly. Once the vapor appears, the cell temperature must be turned down within ~5–30 min or the windows will become permanently coated with a thick layer of lithium. After the cell has been run at operating temperatures for a day or so, it can be valved off from the vacuum pump and placed on an optical bench for use in spectroscopic experiments. The operating lifetime of the hot sapphire windows in the presence of lithium vapor is not infinite, but is sufficiently long for use in an undergraduate lab.

We built several cells of this construction with only modest results. Some disadvantages of the design include the price of the sapphire windows, the high window temperature required, and the limited optical access. We also had some trouble getting the lithium density high enough (optical depth of at least unity in the resonance lines) without problems from lithium plating the windows. Cells shorter than ~15 cm were especially problematic in this regard, plus they needed to be operated very close to 400 °C, which is the maximum safe operating temperature of the sapphire windows. Finally, it is worth mention that it is difficult (and potentially dangerous) to sight down a laser beam to see a

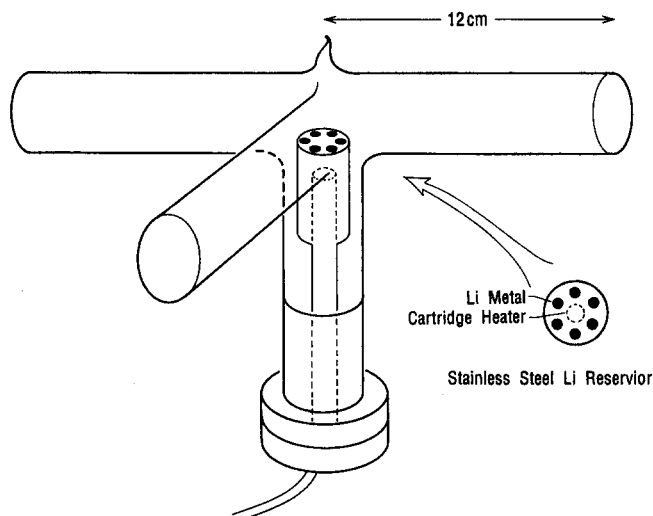


Fig. 7. A “6-shooter” lithium atomic vapor cell. The cartridge heater oven produces thermal lithium atoms, which are kept off the windows by an argon buffer gas. Laser beams propagate along the axis of the cell, and the third leg is for viewing the lithium fluorescence.

lithium fluorescence, although the undergraduate students (and others) all enjoy seeing the fluorescence by this direct method.

Another possible lithium atomic vapor source is a heat-pipe oven.²⁵ With this configuration the cell windows operate at a lower temperature than with a bare cell, and very high vapor densities can be realized. We did not explore this option in detail, since it has many of the same disadvantages as the simple cell design.

We obtained by far our best overall results using the cell design shown in Fig. 7, which we call a lithium “6-shooter.” This design is exceedingly forgiving in its construction and remarkably robust in operation. Lithium is prepared as above and then packed into six holes in a stainless steel bar, surrounding a central cartridge heater.²⁶ The bar is welded to a thin-walled stainless steel tube, typically 0.04-in. wall thickness, which in turn is welded to an UHV flange. The lithium is surrounded by a Pyrex cell, attached via a glass-to-metal seal to another UHV flange. The lithium and heater are thermally isolated by the thin-walled tube, so during operation the cell walls and stem are relatively cool, although still too hot to touch. Note also that the cartridge heater operates outside the vacuum, so it easily connects to its power supply (a variable transformer). A built-in thermocouple monitors the temperature of the cartridge heater, allowing one to repeatedly set the lithium atomic density.

To assemble the cell we attached another vacuum flange to the cell via a narrow glass pinch-off point. Lithium is first packed in the reservoir holes in a nitrogen atmosphere, and the cell is attached to the reservoir assembly. After pumping out the cell with a turbo pump and mildly baking it, a buffer gas of ~150 mTorr of argon is added to the cell to keep lithium gas away from the cell windows. To add argon, a regulated gas bottle was attached to the vacuum manifold via a needle valve. With the turbo pump on, the needle valve is opened slightly and the pressure monitored with a thermocouple vacuum gauge.

With the buffer gas in place, the lithium is heated until the

metal coats the inner walls of the cell. Since the lithium gas must diffuse through the cell, it deposits almost completely on the walls of the cell, with very little reaching the windows. If a small amount of lithium does become plated on the windows, it can be gently baked off (and deposited on the cell walls) at fairly low temperature. Heating the glass to high temperatures to remove deposited lithium tends to cause a chemical reaction that bonds the lithium to the glass, making it permanently opaque. After running for about an hour at this temperature, the buffer gas is pumped out and replaced with ~ 50 mTorr of clean argon, and the pinch-off point is melted with a torch to seal off the cell. With 50 mTorr of argon buffer gas, the mean-free-path of lithium atoms is small enough to prevent plating on the cell windows, but the mean-free time between collisions is not short enough to appreciably pressure broaden the lithium resonance lines.

This cell design is relatively easy to build, although it does require substantial welding and glassblowing expertise. We have our welding done by a local commercial welder with experience welding UHV components, and our glassblowing is done either by a university glassblower or by another local commercial firm. We pinch off the cells ourselves using a small oxy-propane torch that is available at most home-improvement stores.

The lithium cell does not require fancy windows (although one might desire very flat windows or windows at Brewster's angle for special experiments), and is less expensive than other designs. It also offers a long operating life, and is especially robust and easy to operate. Our first cell of this design has been running for hundreds of hours over several years without problems.

We finally note that it is advantageous to add a third leg to the cell, as shown in Fig. 7, for conveniently observing lithium fluorescence brought about by a resonant 670 nm laser.

VI. DISCUSSION

We have implemented both the 670 nm diode lasers and lithium cells described here in a new senior-level undergraduate physics laboratory at Caltech, which consists of a series of experiments in atomic and optical physics. We have found this to be a demanding environment for a new technology, since for the lab to be successful the students must be able to come in and complete a complex experiment, in one try, in about 3–5 h. The lasers and lithium cells have been reliable and fairly straightforward to use in this environment, and we feel that our efforts can be reproduced and extended in many existing undergraduate laboratories.

However, we have also found that our 670 nm lasers are considerably more difficult to assemble and operate than near-IR lasers. The principal disadvantages are the necessity to AR coat the laser's output facet, and the difficulty of tuning the lasers to the lithium resonance lines. 780 nm lasers, by comparison, require no additional AR coating, respond very well to grating feedback, and are relatively easier to tune. In addition, rubidium cells can be used at room temperature. A novice instructor wishing to explore tunable diode laser technology for a teaching laboratory might well be advised to first start with near-IR lasers, as described by MacAdam *et al.*,¹ where the technical hurdles are not so great.

It is certainly possible that with different 670 nm lasers, especially newer higher-power versions, one could substantially reduce the technical difficulties now generally associ-

Lithium Saturated Absorption Spectrum

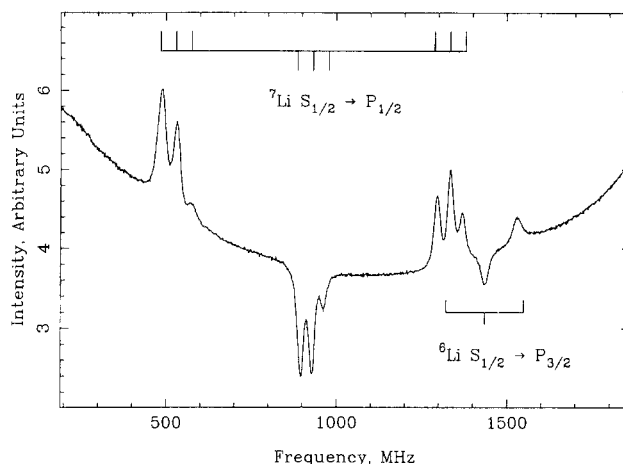


Fig. 8. A saturated absorption spectrum of lithium (with natural abundances), showing Doppler-free peaks from both ^7Li and ^6Li superposed on the Doppler-broadened absorption profile. Tick marks show modeled relative positions for the various resonance and cross-over peaks, from the energy levels in Fig. 1. That the model does not perfectly match the data is probably the result of a distortion of the frequency scale, which here was assumed proportional to the PZT voltage applied to scan the diode's feedback grating.

ated with visible diode lasers. We have by no means explored every possibility for improving the performance of lasers at these wavelengths. Further experimentation may yield inexpensive 670 nm diode laser systems that are as easy to construct and use as near-IR lasers. If that were the case, then in our experience visible lasers would be clearly preferred over near-IR lasers for the undergraduate laboratory.

As an example of what these laboratory teaching tools can do, Fig. 8 shows a lithium saturated absorption spectrum obtained with our diode laser system. Note that this one oscilloscope trace includes both the $^7\text{Li } 2S_{1/2} \rightarrow 2P_{1/2}$ and the $^6\text{Li } 2S_{1/2} \rightarrow 2P_{3/2}$ lines, along with their hyperfine structure and crossover resonances, superimposed on the broad Doppler width of the spectral lines. Details of this and other undergraduate lab experiments that can be done with 670 nm lasers and lithium cells will be presented in future publications.

ACKNOWLEDGMENTS

This work was supported in part by the National Science Foundation ILI Program, an AT&T Special Purpose Grant, and the California Institute of Technology. We thank H. J. Kimble for making available the resources of the Caltech Quantum Optics Group, without which this work could not have been done.

^aPresent address: Physics Department, Stanford University, Stanford, CA 94305.

^bPresent address: Physics Department, University of Illinois, 1110 West Green St., Urbana, IL 61801.

¹K. B. MacAdam, A. Steinbach, and C. Wieman, "A narrow-band tunable diode-laser system with grating feedback, and a saturated absorption spectrometer for Cs and Rb," *Am. J. Phys.* **60**, 1098–1111 (1992).

²New Focus Inc., 1275 Reamwood Ave., Sunnyvale, CA 94089. Turn-key diode laser systems are available for approximately \$12 000.

³Environmental Optical Sensors, Inc., 6395 Gunpark Dr., Boulder, CO 80301. Turn-key diode laser systems are available for approximately

- \$12 000; vapor cells are available for approximately \$250 (rubidium standard cell) to \$750 (lithium cell).
- ⁴M. G. Boshier, D. Berkeland, E. A. Hinds, and V. Sandoghdar, "External-cavity frequency-stabilization of visible and infrared semiconductor lasers for high-resolution spectroscopy," *Opt. Commun.* **85**, 355–359 (1991).
- ⁵J. C. Camparo, "The diode laser in atomic physics," *Cont. Phys.* **26**, 443–477 (1985).
- ⁶Part T9215 diode laser, Thor Labs, P. O. Box 366, Newton, NJ 07860. Price per laser is approximately \$80.
- ⁷R. D. Mathis Co., 2840 Gundry Ave., Long Beach, CA 90806.
- ⁸Newark Electronics, 12631 E. Emperial Hwy., Santa Fe Springs, CA 90670.
- ⁹Part 6-500 transformer, Signal Transformer, 500 Bayview Ave., Inwood, NY 11696.
- ¹⁰Part 3344-MSP-A4164 V-60 Turbopump Station with built-in pump and MultiGage Controller, Varian Vacuum Products, 121 Hartwell Ave., Lexington, MA 02173. The station price is approximately \$6000.
- ¹¹C. E. Wieman and L. Hollberg, "Using diode lasers for atomic physics," *Rev. Sci. Instrum.* **62**, 1–20 (1991).
- ¹²K. C. Harvey and C. J. Myatt, "External-cavity diode-laser using a grazing-incidence diffraction grating," *Opt. Lett.* **16**, 910–912 (1991).
- ¹³Part CP1.4-71-10L thermoelectric cooler, Melcor, 1040 Spruce St., Trenton, NJ 08648.
- ¹⁴C. C. Bradley, J. Chen, and R. G. Hulet, "Instrumentation for the stable operation of laser diodes," *Rev. Sci. Instrum.* **61**, 2097–2101 (1990).
- ¹⁵K. G. Libbrecht and J. L. Hall, "A low-noise high-speed diode-laser current controller," *Rev. Sci. Instrum.* **64**, 2133–2135 (1993).
- ¹⁶PZT Tube C-5500, 0.035 in. wall, 0.5 in. O.D., 0.5 in. diam, Channel Industries Inc., 839 Ward Dr., Santa Barbara, CA 93111.
- ¹⁷P. Horowitz and W. Hill, *The Art of Electronics*, 2nd ed. (Cambridge University Press, Cambridge, 1989), p. 169.
- ¹⁸A. Yariv, *Optical Electronics*, 4th ed. (Holt, Rinehart, and Winston).
- ¹⁹Part 43 221 holographic grating, Edmund Scientific Co., 101 E. Gloucester Pike, Barrington, NJ 08007.
- ²⁰A. T. Schremer and C. L. Tang, "External-cavity semiconductor-laser with 1000 GHz continuous piezoelectric tuning range," *IEEE Photonics Technol. Lett.* **2**, 3–5 (1990).
- ²¹Part WA-2000 Wavemeter-jr, Burleigh Instruments Inc., P.O. Box E, Fishers, NY 11453. Price is approximately \$6000.
- ²²MDC Vacuum Products Corp., 23842 Cabot Blvd., Hayward, CA 94545.
- ²³M. Kasevich, private communication.
- ²⁴In the presence of moisture, lithium in a nitrogen atmosphere can react to form the nitride. This is an exothermic reaction, which can run away, ruining one's lithium samples. We have seen this happen once, but typically we have no problems filling a leaky glove box with an overpressure of nitrogen from the boil-off of a liquid nitrogen dewar. An argon atmosphere could be used to eliminate this potential problem.
- ²⁵R. Hulet (private communication).
- ²⁶Part E1A53 cartridge heater with thermocouple, type J, style C, Watlow, 12001 Lackland Rd., St. Louis, MO 63146.
- ²⁷Z. Lin, K. Shimizu, M. Zhan, F. Shimizu, and H. Takuma, "Laser cooling and trapping of lithium," *Jpn. J. Appl. Phys.* **30**, L1324-L1326 (1991).

Understanding the chemical potential

G. Cook and R. H. Dickerson

Physics Department, California Polytechnic State University, San Luis Obispo, California 93407

(Received 11 August 1994; accepted 14 February 1995)

When teaching thermal physics and statistical mechanics the authors find a lot of confusion among students about the meaning of the chemical potential μ . It seems particularly difficult for students to develop a physical picture of what μ is. In this paper some simple, pedagogical models are developed to make the meaning of μ clear, for a few selected systems. © 1995 American Association of Physics Teachers.

I. INTRODUCTION

After several years of teaching thermal physics and statistical mechanics to undergraduates, the authors find that there is still a lot of confusion about the meaning of the "chemical potential," μ . Typically, students learn the definition of μ , its properties and consequences, and work problems using it, but often still ask "But what is it?" In this paper we try to clarify the meaning of μ .

II. GENERAL DISCUSSION OF CHEMICAL POTENTIAL

Consider a system which can exchange energy and particles with a reservoir, and the volume of which can change. Energy acquired by the system, through heating, increases its internal energy, U , by TdS , where T is the temperature of the system, and S is the entropy of the system. If the system expands by volume dV at pressure p , the work done by the system is pdV . If the system gains dN particles (all of one

single type), then U increases by μdN , where μ is the chemical potential. The change in the internal energy is then

$$dU = TdS - pdV + \mu dN. \quad (1)$$

This relation is commonly called the thermodynamic identity, valid for infinitesimal, reversible processes.

It follows that

$$\mu = \left. \frac{\partial U}{\partial N} \right|_{S,V}. \quad (2)$$

We would like to look at what Eq. (2) tells us for some simple systems.

A. A system of distinguishable, classical particles

Consider a simple, idealized system. Suppose the single particle energy eigenvalues are quantized in integer multiples of energy ϵ , as shown in Fig. 1. In general, ϵ will depend on the volume, V , of the system, but we will insist on holding V