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Modern Spectroscopy with a Spectrometer by the Optogalvanic Effect

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constant of the liquid. The wave function of the electrons moving in this "one-dimensional hydrogenic" potential has a z dependence of the form $zR_{n0}(z)$ with $Z = (\epsilon - 1)/4(\epsilon + 1) \approx 10^{-2}$. The electrons can move freely in directions parallel to the surface and their energies are given by

$$E_n = (\hbar^2 K^2/2m) - Z^2 e^2/2a_0 n^2,$$

$\hbar K$ being the momentum parallel to the layer. For each n one gets a band of energies (the so-called sub-band) corresponding to the parallel motion. If a magnetic field is applied parallel to the layer it contributes an additional term $e^2B^2z^2/8mc^2$ to the Hamiltonian and the second-order correction to the energy in the lowest sub-band is again given by Eq. (16) with $b = 0$ and $a = e^2B^2/8mc^2$. Since Z is now very small, the energy correction would be quite significant for B of the order of 10^5 G. One can experimentally "see" this change by measuring the inter-sub-band transition frequencies of the layer in presence of a magnetic field of such strength. For example, the frequency of transition from the second to the first sub-band is given by

$$\omega = (E_2' - E_1')/\hbar,$$

where E_2' is the energy of electrons in the second sub-band with the B field on. Although we have not given an expression for the second-order correction to E_2, our calculations can be very easily extended to this case. Thus ω can be theoretically calculated and compared with the experiment. In fact, our approach based on the conventional perturbation method has the advantage here over the F-operator method given in Ref. 3 because it is not clear whether E_1', E_2' can be calculated for Q2D systems using the latter method.

The experiments of the type described above have actually been undertaken and small shifts of the transition frequencies due to the magnetic field have been observed[7]; however, in these experiments a perpendicular electric field was applied to the layer in addition to the magnetic field and furthermore, the variation of the linewidth of the absorption lines was of more interest. It should not be difficult to repeat such experiments and make an analysis of the frequency shifts as a function of the B field.

We would like to conclude by pointing out that, if $B \sim B_c$ or if $B > B_c$, which is the case for hydrogen atoms in magnetic fields of the order of 10^{10} G or larger (present in high-density stars), one must treat the problem in an entirely different way and we have found several works in this area.[8,9] For such large fields, the magnetic energy is the dominating contribution while the Coulomb energy can be treated as a perturbation.

[1]See, e.g., L. I. Schiff, *Quantum Mechanics*, 3rd ed. (McGraw-Hill, New York, 1968), p. 252.

[2]L. I. Schiff and H. Snyder, Phys. Rev. **55**, 59 (1939).

[3]P. Lambin, J. C. Van Hay, and E. Kartheuser, Am. J. Phys. **46**, 1144 (1978).

[4]A. R. Ruffa, Am. J. Phys. **41**, 234 (1973).

[5]H. A. Bethe and E. E. Salpeter, *Quantum Mechanics of One- and Two-Electron Atoms* (Plenum, New York, 1977), p. 265.

[6]See M. W. Cole, Rev. Mod. Phys. **46**, 451 (1974) and references therein.

[7]C. L. Zipfel, T. R. Brown, and C. C. Grimes, Phys. Rev. Lett. **37**, 1760 (1976).

[8]See, e.g., Y. Yafet, R. W. Keyes, and E. N. Adams, J. Phys. Chem. Solids **1**, 137 (1956).

[9]An interesting description of phenomena near $B \sim B_c$ has been given by A. R. P. Rau, Phys. Rev. A **16**, 613 (1977).

Modern spectroscopy with a spectrometer by the optogalvanic effect

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An experiment involving the optogalvanic effect suitable for the advanced physics laboratory is described. This experiment complements the usual basic experiment in atomic spectroscopy where spectra are recorded on photographic film with a spectrograph or with a monochromator and photomultiplier. The optogalvanic effect used the atoms being studied as the detector and a tunable dye laser as the source. Linewidths observed are those of the dye laser that are considerably smaller than those obtained with the usual laboratory monochromator. The student is introduced to the techniques of spectroscopy with pulsed dye lasers and to a spectrum for which *LS* coupling does not hold.

INTRODUCTION

In this experiment the spectrum of neon will be studied with both conventional spectrographic techniques and the optogalvanic effect. These will graphically demonstrate the higher resolution obtainable with the optogalvanic effect. The optogalvanic effect uses the atom whose spectrum is being determined as the detector. The basic idea is that when atoms in a discharge absorb radiation they are either more or less easily ionized than before and hence the resistance of the discharge changes. The change in resistance is detected as a change in voltage across the discharge as a dye laser is tuned across an absorption line.

In performing this experiment, the student will become acquainted with conventional spectrographic techniques, dye lasers, the technique of spectroscopy with pulsed lasers, the spectrum of neon that does not show the usually studied *LS* coupling, as well as the optogalvanic effect. The pulsed laser used was borrowed from a research laboratory, but a pulsed xenon ion laser has been constructed by students in

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our advanced physics laboratory and a dye laser is under construction.

OPTOGALVANIC EFFECT

The optogalvanic effect was first observed in the study of electric discharges illuminated with light from the same gas.[1-3] If the radiation absorbed in the discharge produces a transition to a higher state from which ionization by electron collision proceeds more easily, then the electron temperature, discharge impedance, and voltage across the discharge decrease. Conversely, if the absorbed radiation depletes a long-lived metastable state from which the atoms can be more easily ionized by collision, then the discharge electron temperature, discharge impedance, and voltage across the discharge increase. Penning[1] and Meissner and Miller[2] studied this latter effect in a rare gas discharge and Kenty[3] studied it in a Hg vapor lamp when the discharge was irradiated from another Hg discharge. Bell and Bloom[4] studied this effect in He and developed a crude 2-μm radiation detector.

The optogalvanic effect has also been observed when gas lasers begin to lase. Garscadden and co-workers,[5,6] Schiffner and Seifert,[7] and Weaver[8] have observed the change in voltage across a HeNe laser when it began to lase. The effect has been observed also in inert gas ion lasers.[9,10] In CO_2 lasers,[11] the effect can be so pronounced that under certain operating conditions the discharge can be extinguished. Skolnik[12] has used the large optogalvanic signal in CO_2 discharge lasers to frequency stabilize them to the center of the gain line.

Green has demonstrated the power of the optogalvanic effect in both high-resolution spectroscopy and in analytic chemistry. Green *et al.*[13] have irradiated seeded flames with the radiation from a chopped cw dye laser. The flame passed between a pair of closely spaced electrodes and was irradiated in this region. The laser was chopped or modulated so the change in voltage was similarly modulated and was capacitively coupled into a lock-in amplifier. Seeded material in concentrations of ppb were easily detected. Green *et al.*[14,15] studied in detail the optogalvanic signals from neon hollow cathodes with various added impurities in the cathode (spiked). In particular, they studied the optogalvanic signals from Ne, Li, Na, Ca, Ba, and U. Several of these hollow cathodes were commercially purchased.

King *et al.*[16] demonstrated that the optogalvanic signal from a spiked neon hollow cathode can be used to wavelength calibrate a pulsed or cw dye laser and determine the laser bandwidth. They studied hollow cathodes filled with He, Ne, and Ar carrier gases and spiked with Al, Fe, Hg, Li, Na, Ca, Ba, and U. Using several different hollow cathodes, a laser can be calibrated from 260 to 655 nm. A portion of the laser light is deflected into the hollow cathode and the signal is measured. If a chopped cw dye laser is used as the pump source, the detector is a lock-in amplifier. If a pulsed dye laser is used as a source, the wavelength calibration can be measured by observing the optogalvanic signal on an oscilloscope. This latter technique does not allow the measurement of the bandwidth of the line since the line shape is recorded only at its maximum intensity. If the atomic line is not appreciably Doppler or pressure broadened by the discharge temperature or the carrier gas pressure, the atomic linewidth is narrower than the laser line width and the recorded spectral lines exhibit the line width of the laser pump source.

Schenck and co-workers[17,18] have studied the neon optogalvanic effect in spiked neon hollow cathodes in detail. Recently, they have studied flames seeded with Sc_2O_3, $YCl_3 0.6H_2O$, and $La(NO_3)0.6H_2O$. The flame was between sets of electrodes and was irradiated with a nitrogen-pumped dye laser. This signal was detected using a fast FET amplifier and a boxcar signal averager triggered from the laser.

Smyth and co-workers[19,20] have studied both high- and low-current hollow cathodes and have devised a special hollow cathode. Using this hollow cathode they measured the neon ion concentration with a time-of-flight mass spectrometer. Zalewski *et al.*[21] performed very elaborate studies on the optogalvanic effect from a neon hollow cathode. Bridges[10] has written an excellent and extensive paper on the effect where dc discharges, hollow cathodes, and even an 0A3 tube were investigated.

Miron *et al.*[22] were the first people to observe the optogalvanic signal from a hollow cathode pumped by a pulsed dye laser. Lawler *et al.*[23] performed the first Doppler-free intermodulation optogalvanic experiment. Feldman[24] was the first person to study the laser-induced optogalvanic signal from a discharge containing the molecules: NH_3, NO_2, H_2, N_2, O_2, and Ar.

In this laboratory experiment the emission spectra from a neon hollow cathode is measured using a monochromator and photomultiplier detector. Then the optogalvanic voltage changes are measured when the same hollow cathode is irradiated by a dye laser that is scanned in wavelength. Optogalvanic spectra are recorded using a gated sample-hold unit and by this technique actual line shapes are recorded. The magnitude of the optogalvanic voltage change was also measured using an oscilloscope. The latter technique is less expensive than the previous and allows the accurate measurement of the neon wavelengths and signal magnitudes. In the optogalvanic experiments a nitrogen-pumped dye laser will be used as the pump source for these lasers can actually be constructed at small colleges. Finally, the conventional neon emission spectra will be compared with the optogalvanic spectra.

SPECTRUM OF NEON

The energy levels of neon do not obey either of the two coupling schemes usually studied in an undergraduate atomic physics course [namely, (**L·S**) or (**jj**)] but rather intermediate (**jl**) coupling[25] holds. Intermediate coupling results in the energy levels being grouped in pairs instead of the multiplet structure of (**L·S**) coupling. The spectrographic notation of these energy levels was assigned by Paschen[26,27] in 1918 before there was an understanding of quantum mechanics and atomic spectra. However, this notation is unusual and does not give the student a physical meaning of the coupling scheme. The ground-state level of all inert gases is a $^1S_0$ state. In the first excited state of neon, one $2p^6$ electron is excited to the $3s$ state and this configuration $1s^2 2s^2 2p^5 3s$ gives rise to four energy levels. Paschen designated these as the $1s_2$, $1s_3$, $1s_4$, and $1s_5$ states. As (**L·S**) coupling is nearly valid for these first excited states, they correspond to $^1P_1$, $^3P_0$, $^3P_1$, and $^3P_2$ states of (**L·S**) coupling. The second group of excited states arises from the electron configuration $1s^2 2s^2 2p^5 3p$. There are ten energy levels designated the $2p_1 \cdots 2p_{10}$ states by Paschen. For these states

Table I. Excited energy levels of Ne I.

Paschen notation	Electron configuration	Designation	Energy[2] (cm)	Energy (eV)	J	Approx. (L·S) notation
	$2p^6$	$2p^6\,{}^2S_0$	0	0	0	$^1S_0$
$1s_5$	$2p^5(^2P_{1\frac{1}{2}^o})3s$	$3s\,(1\frac{1}{2}^o)$	134043.790	16.62	2	$^3P_2$
$1s_4$	$2p^5(2P_{1\frac{1}{2}^o})3s$	$3s\,(1\frac{1}{2}^o)$	134461.237	16.67	1	$^3P_1$
$1s_3$	$2p^5(^2P_{\frac{1}{2}^o})3s$	$3s\,(\frac{1}{2}^o)$	134820.591	16.72	0	$^3P_0$
$1s_2$	$2p^5(^2P_{\frac{1}{2}^o})3s$	$3s\,(\frac{1}{2}^o)$	135890.670	16.85	1	$^1P_1$
$2p_{10}$	$2p^5(^2P_{1\frac{1}{2}^o})3p$	$3p\,(\frac{1}{2})$	148259.746	18.38	1	
$2p_9$	$2p^5(^2P_{1\frac{1}{2}^o})3p$	$3p\,(1\frac{1}{2})$	149659.000	18.56	3	
$2p_8$	$2p^5(^2P_{1\frac{1}{2}^o})3p$	$3p\,(1\frac{1}{2})$	149826.181	18.58	2	
$2p_7$	$2p^5(^2P_{1\frac{1}{2}^o})3p$	$3p\,(1\frac{1}{2})$	150123.551	18.61	1	
$2p_6$	$2p^5(^2P_{1\frac{1}{2}^o})$	$3p\,(1\frac{1}{2})$	150317.821	18.64	2	
$2p_5$	$2p^5(^2P_{\frac{1}{2}^o})3p$	$3p\,(1\frac{1}{2})$	150774.072	18.69	1	
$2p_4$	$2p^5(^2P_{\frac{1}{2}^o})3p$	$3p\,(1\frac{1}{2})$	150860.468	18.70	2	
$2p_3$	$2p^5(^2P_{1\frac{1}{2}^o})3p$	$3p\,(\frac{1}{2})$	150919.931	18.71	0	
$2p_2$	$2p^5(^2P_{\frac{1}{2}^o})3p$	$3p\,(\frac{1}{2})$	151040.413	18.73	1	
$2p_1$	$2p^5(2P_{\frac{1}{2}^o})$	$3p\,(\frac{1}{2})$	152972.697	18.97	0	

(jl) coupling is appropriate and **J** is a good quantum number to designate the states.

One can think of the neon electron configuration $1s^22s^22p^5$ as the configuration of Ne II (ionized neon) and the two lowest energy states are the $2P_{1\frac{1}{2}^o}$ and $2p_{\frac{1}{2}^o}$ and the Ne I configuration $1s^22s^22p^53p$ is just the addition of a p electron to ionized neon. This added p electron has a j value of $1\frac{1}{2}$ and $\frac{1}{2}$ and its addition to the $^2P_{1\frac{1}{2}^o}$ and $^2P_{\frac{1}{2}^o}$ states give rise to four groups of energy levels:

$$(^2P_{1\frac{1}{2}^o})\,p_{1\frac{1}{2}} \qquad \text{with } J = 3, 2, 1, 0;$$

$$(^2P_{1\frac{1}{2}^o})\,p_{\frac{1}{2}} \qquad \text{with } J = 2, 1;$$

$$(^2P_{\frac{1}{2}^o})\,p_{1\frac{1}{2}} \qquad \text{with } J = 2, 1;$$

Table II. Neon transitions studied.

Paschen transition	$J' \rightarrow J'$	Wavelength (nm)
$1s_3$–$2p_2$	$(0 \rightarrow 1)$	616.36
$1s_3$–$2p_5$	$(0 \rightarrow 1)$	626.65
$1s_4$–$2p_2$	$(1 \rightarrow 1)$	603.00
$1s_4$–$2p_3$	$(1 \rightarrow 0)$	607.43
$1s_4$–$2p_4$	$(1 \rightarrow 2)$	609.62
$1s_4$–$2p_5$	$(1 \rightarrow 1)$	612.85
$1s_4$–$2p_6$	$(1 \rightarrow 2)$	630.48
$1s_5$–$2p_2$	$(2 \rightarrow 1)$	588.19
$1s_5$–$2p_4$	$(2 \rightarrow 2)$	594.48
$1s_5$–$2p_5$	$(2 \rightarrow 1)$	597.55
$1s_5$–$2p_6$	$(2 \rightarrow 2)$	614.31
$1s_5$–$2p_7$	$(2 \rightarrow 1)$	621.73
$1s_5$–$2p_8$	$(2 \rightarrow 2)$	633.44

$$(^2P_{\frac{1}{2}^o})\,p_{\frac{1}{2}} \qquad \text{with } J = 1, 0.$$

These energy states can now be grouped in pairs and in Table I we list these energy states in Paschen notation, electron configuration designation, energy in cm^{-1}, energy in eV, J, and an equivalent (L·S) coupling term for the $1s$ levels. In the electron configuration the $1s^22s^2$ electrons are understood in the table.

Because the neon energy levels are best described by (jl) coupling, the familiar (L·S) coupling selection rules do not apply. The selection rule is that J change by 0 or ± 1, with $J = 0 \leftrightarrow J = 0$ transition excluded. Application of this selection rule to the levels shown in Table I yields the allowed transitions shown in Table II. An energy level diagram for these $1s$–$2p$ levels is shown in Fig. 1.

Because the $1s$ states are reasonably well described by (L·S) coupling we can analyze transitions between the $1s$ states and the ground state using (L·S) coupling dipole se-

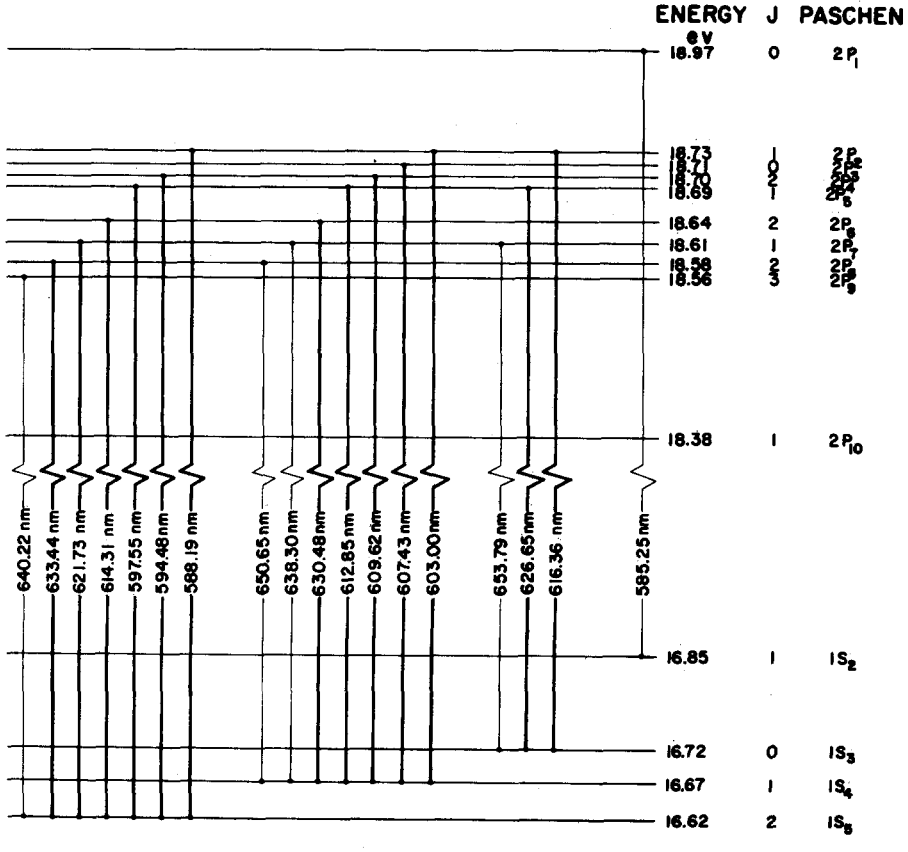

Fig. 1. Energy-level diagram of the first and second excited states of neon.

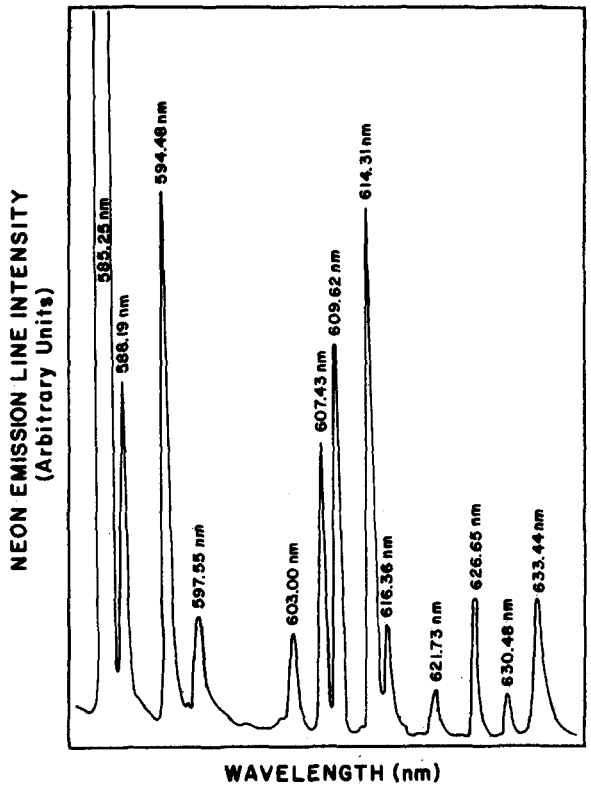

Fig. 2. Conventional emission spectrum of neon from 585 to 634 nm.

lection rules $\Delta S = 0$; $\Delta L = 0, \pm 1$; and $\Delta J = 0, \pm 1$ ($0 \rightarrow 0$ forbidden). One finds that the ground state to $^1P_1$ ($1s_2$) state is allowed, while the ground state to $^3P_2$ ($1s_5$), $^3P_1$ ($1s_4$) and $^3P_0$ ($1s_3$) states are all forbidden. Thus these latter three states are metastable.

EXPERIMENT AND RESULTS

Conventional emission spectra are taken first with a ½-m Bausch and Lomb monochromator with a 600-line/mm grating, a 931A photomultiplier, a Hewlett Packard 6516-mV ammeter, Keithley 153-mV ammeter, and a Gould chart recorder. The monochromator was visually wavelength calibrated using a Hg light source. The usual spectral analysis of several Osram sources was performed to acquaint the students with the instrument. The hollow cathode discharge was a standard Jarrell Ash lamp that was barium spiked and contained neon as the carrier gas. The neon spectrum was recorded between 585 and 640 nm and is shown in Fig. 2. The hollow cathode was operated with 250 V between the cathode and anode and a current of 15 mA. The current to the hollow cathode is limited with a fixed 4000-Ω resistor in series with a variable 3000-Ω resistor. The monochromator has a linear dispersion of 3.3 nm/mm and slits were set at 0.5 mm so two lines separated by 1.7 nm could be resolved. If the spectrum is carefully analyzed the representative half maximum bandwidth of the spectral lines was 0.86 nm. This number is based on the most intense and distinct lines observed in our spectra that were the lines at 626.65, 614.31, 609.62, 594.48, and 588.19 nm. The spectrum in Fig. 2 has not been corrected for the sensitivity of the photomultiplier. The spectrum and linewidth of the spectral lines were of interest so this spectrum could be compared to the optogalvanic spectrum.

The optogalvanic effect can be observed using an argon ion laser pumped cw dye laser and a light chopper. The hollow cathode is a commercial tube and the voltage changes can be observed on a lock-in amplifier and recorded with a chart recorder. An argon ion laser pumped dye laser system is very expensive and most schools will not have one available for use by the undergraduate student.

On the other hand, many schools have pulsed nitrogen-pumped dye lasers in their research laboratory or such a laser can be easily constructed.[29,30] Also a dye laser can be pumped by a pulsed xenon ion laser.[31,32] Both pulsed nitrogen-pumped and xenon-ion-pumped dye lasers have been constructed in the special problems course by undergraduate students at Rolla. During the spring semester a xenon ion laser was constructed at Rolla in our advanced laboratory. In a future semester the dye laser will be assembled and this laser will be used to observe the optogalvanic effect and other photophysics experiments.

The laser used in this experiment was a Molectron UV-1000 nitrogen laser that pumped a Molectron DL-200 dye laser. A Jarrell Ash hollow cathode that was axially irradiated by the laser. Neon was the carrier gas and the lamp was spiked with barium. The change in voltage across the tube was either capacitively coupled into a Tektronix 555 oscilloscope or a Molectron sample hold unit that consisted of a 122 dual gate generator, a 112 differential gated integrator (sample-hold unit), and a 131 amplifier. The laser, samplehold unit, and oscilloscope are triggered from a Hewlett Packard 202A low-frequency signal generator. The apparatus is shown schematically in Fig. 3.

The region from 588 to 634 nm was scanned by using two dyes, Rhodamine 6G from 588 to 602 nm and Rhodamine B from 602 to 635 nm. The hollow cathode was operated at 250 V and the discharge current could be varied from 5 to 15 mA by adjusting the variable resistor. As the laser was scanned, atoms of neon absorbed the radiation at the wavelengths corresponding to the $1s$–$2p$ transitions. The resistance of the discharge changes when the neon atoms absorb the laser radiation, resulting in voltage change across the hollow cathode lamp.

The optogalvanic voltage change ranges from tenths of millivolts to volts when the hollow cathode is operated at 250 V and can easily be seen on the scope. If an oscilloscope is used, the line profile of the optogalvanic signal cannot be determined, but the maximum amplitude of the voltage change and the wavelength of the line can be easily determined. If the scan drive on the laser is calibrated as it is on the Molectron laser, the line can be detected on the oscilloscope and the wavelength determined from the scan drive reading. If a home-made dye laser is used, a monochromator must be calibrated and some filtered laser radiation must be sent into it and the wavelength read from the monochromator drive. Some representative optogalvanic

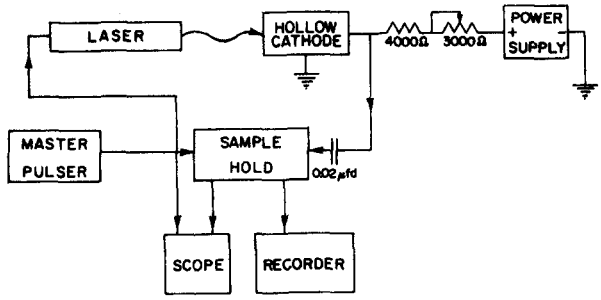

Fig. 3. Schematic of the apparatus.

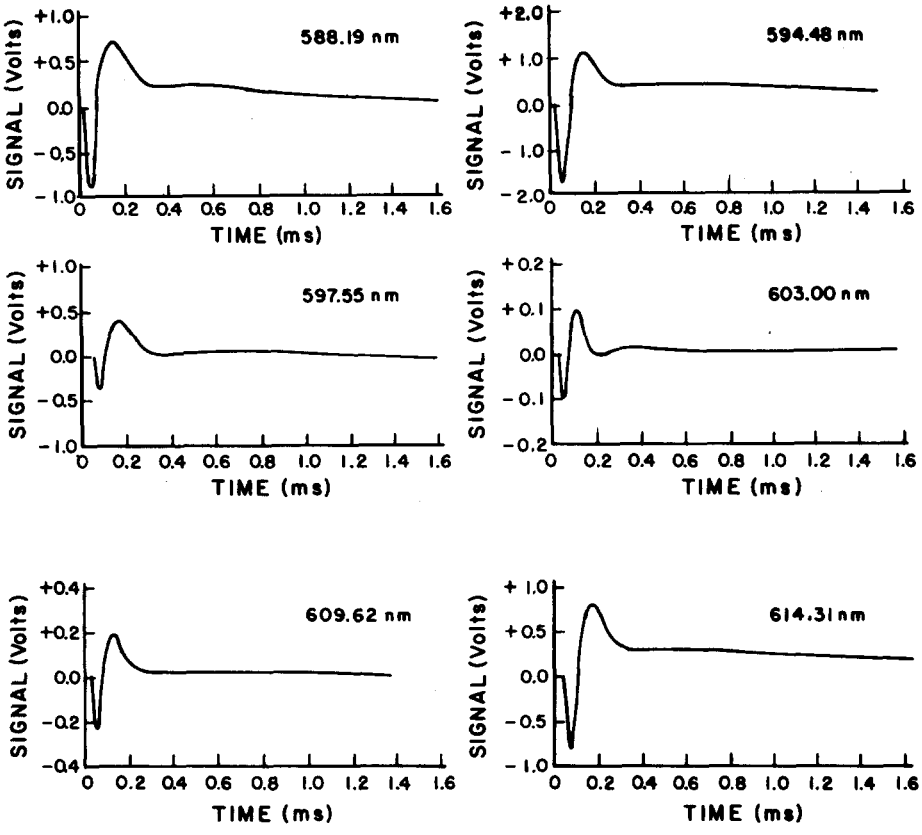

Fig. 4. Optogalvanic data recorded using the oscilloscope detection method.

signals are seen in Fig. 4. These traces were taken with a current of 7 mA. The shape of the signal was found to vary only slightly with increasing discharge current, but the amplitude of the signal decreased appreciably.

If the line profile is also desired, then the line shape must be recorded and the commercial Molectron sample-hold system with a chart recorder readout was used. In these experiments the discharge was operated at 250 V and at currents of 5, 10, and 15 mA. The voltage change across the hollow cathode was capacitivity coupled into the 131 amplifier. The preamplified signal is stored in the 112 differential gated integrator that has two *RC* integrators that integrate the signal and noise over two different sample windows that have been set on the 122 dual gate generator. The position and duration of the window can be manually set by the dual gate generator. One window gate applied to the differential integrator samples the signal at the maximum positive level shown in Fig. 4 and the second window of the same width samples the background level. The output of the differential integrator is the difference of these signals, which can be recorded on a Hewlett Packard 7311A chart recorder. Figure 5 is a typical spectrum when the dyes Rhodamine 6G and 6B were used. The 603.00-nm line was not recorded. Table III records the level of the positive voltage change for several lines as a function of discharge current.

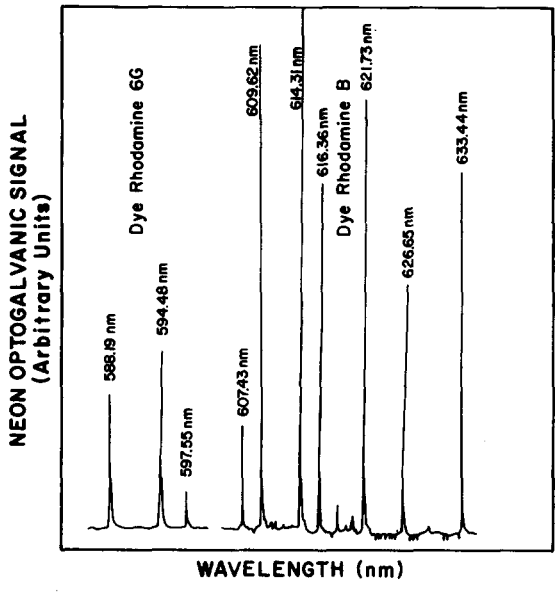

Fig. 5. Optogalvanic line shapes recorded using the sample-hold detection method.

Table III. Optogalvanic signal versus current.

Dye	Wavelength (nm)	Current (mA)	Optogalvanic signal (V)
Rhodamine B	607.43	5	0.260 ± 0.005
		10	0.224 ± 0.005
		15	0.171 ± 0.005
	609.62	5	0.650 ± 0.005
		10	0.550 ± 0.005
		15	0.400 ± 0.005
	614.31	5	0.220 ± 0.005
		10	1.600 ± 0.005
		15	1.100 ± 0.005
	616.36	5	0.550 ± 0.005
		10	0.330 ± 0.005
		15	0.220 ± 0.005
	621.73	5	0.850 ± 0.005
		10	0.580 ± 0.005
		15	0.360 ± 0.005

The pulse from the dye laser is only 15–20 nm wide and the Molectron sample-hold unit cannot resolve pulses this narrow. The output pulses were stretched by the long RC time constant of the discharge and power supply resistor combination and a 0.02-μf capacitor.

DISCUSSION AND CONCLUSION

The initial negative going voltage excursion in Fig. 4 shows that the effect of the absorption of the laser radiation by the metastable neon atoms in the discharge is to initially decrease the resistance of the discharge. This is because the neon atoms are more easily ionized (thus contributing to the discharge current) from the $2p$ states than from the metastable $1s$ states. After the population of the metastable $1s$ state is depleted by laser pumping, the atoms must be ionized from the ground state. The discharge impedance and voltage increase and the signal becomes positive. At the end of the laser pulse the metastable atom population returns to the average population for the dc discharge and the current and voltage return to zero.

The transition from the $1s_2$ state to $2p_1$ state ($\lambda = 585.25$ nm) is not observed in the optogalvanic spectrum. This is because the $1s_2$ level is *not* metastable, and hence no large population of these atoms exists in the discharge for the laser to excite to the $2p_1$ level. Of course the $2p_1$ to $1s_2$ emission is seen in the emission spectrum (Fig. 2).

The Doppler and pressure broadening in the hollow discharge are small compared to the linewidth of the laser (about 0.05 nm), and thus the linewidths observed are those of the laser. In the emission spectrum, the linewidths are those of the monochromator used, about 0.9 nm.

In conclusion this experiment has demonstrated several important principles in atomic physics. Since neon was studied, the student has been exposed to some atomic spectra and selection rules which involve intermediate coupling and are not discussed in the usual atomic physics textbook. This experiment introduced the student to the conventional emission spectroscopy and to optogalvanic spectroscopy. Because a pulsed laser was used, the student also gains familiarity with an alternative to the lock-in amplifier usually used with cw sources.

If a commercial laser is not available this experiment can be developed over several semesters at reasonable cost. Initially the first group could construct a pump laser (pulsed nitrogen or xenon). The next semester a dye laser would be constructed and finally the experiment could be performed in a third semester. Both pulsed nitrogen and xenon ion laser-pumped dye lasers have been constructed by undergraduate students at the University of Missouri-Rolla.[29-32]

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". . . My dear sir—I received your paper, and thank you very much for it. I do not say I venture to thank you for what you have said about 'lines of force,' because I know you have done it for the interests of philosophical truth: but you must suppose it is work grateful to me, and gives me much encouragement to think on. I was at first almost frightened when I saw such mathematical force made to bear upon the subject, and then wondered to see that the subject stood it so well."

Faraday to Maxwell—March 25, 1857