imum current output of our power supply is 100 A. Since most of these laser outputs did not saturate with our power supply, one could expect larger output powers with a bigger current source. Also reported are small-signal gains and new laser transitions in Cu^+, Ag^+, Kr^+, and Ar.

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Pressure Dependence of the Infrared Laser Lines in Barium Vapor

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Abstract—**We have studied nine laser transitions in Ba vapor at wavelengths between 1.13 and 3.05 μm. Three of these laser lines have not been reported previously. The relative intensities of the four strongest transitions (1.13, 1.50, 2.55, and 2.92 μm) vary with buffer gas pressure, suggesting that collisional deexcitation of the $6p\ ^1P_1$ state occurs at higher pressure and is the main mechanism populating the upper states of the 2.55 and 2.33 μm lines.**

METAL vapor lasers have demonstrated a potential for high power and efficiency [1]-[3]. The efficiency results from a favorable ratio of laser photon energy to energy of the upper laser level and a large cross section for electron excitation from the ground state into an upper laser state.

Laser emission in barium vapor was first observed by Cahuzac [4], who identified twenty emission lines. Subsequent work by others [3], [5] have demonstrated average power levels of several watts and electrical to optical conversion efficiencies as high as 0.54 percent. Although the dominant laser transitions produce radiation at 1.50 and 1.13 μm, substantial emission has been observed at several other wavelengths. We have found collisional deexcitation to be important at high buffer gas pressures. The deexcitation quenches some emission lines, but apparently is the excitation mechanism for others.

Fig. 1 is an energy level diagram that includes the eleven dominant laser lines that we observed in Ba vapor. Table I lists these lines and our assignments of the upper and lower laser levels; we are confident of the assignments of the first nine lines, but the final two assignments are less certain.

Fig. 2 is a partial energy level diagram that includes those transitions whose intensities exhibit a dependence on buffer gas pressure. The Born approximation predicts that the $^1P_1$ and $^3P_1$ levels will be pumped predominantly. We observed laser emission on four of the six transitions allowed from these states, including one line that has not been observed previously. This line, and two other new laser lines previously seen only in spontaneous emission, are marked with asterisks in Table I.

For this study, an alumina tube—76 cm long, 9.2 mm ID, and fitted with Brewster-angle sapphire windows—was employed as the discharge vessel. An oven heated the central 40 cm of the tube to approximately 950°C so that the barium density was independent of repetition rate. Excitation was provided by discharging a 1.0 nF capacitor through the laser using an E. G. & G. 1802 thyratron. The capacitor was resonantly charged through a high-voltage diode and a 10 μH inductor from a 10 kV power supply. The maximum repetition rate was limited to 2 kHz by the thyratron trigger. The optical cavity was formed by a 1 in gold coated flat and a 1 in uncoated sapphire flat.

Figs. 3 and 4 report the results of our pressure dependence studies; only the four strongest lines are shown for clarity. There are several interesting features which indicate that collisional processes dominate the coupling of these low-lying multiplet levels. Pressures were measured with either a mercury or an oil manometer, and the intensities are simply the detector voltages uncorrected for the PbSe detector responsivity or

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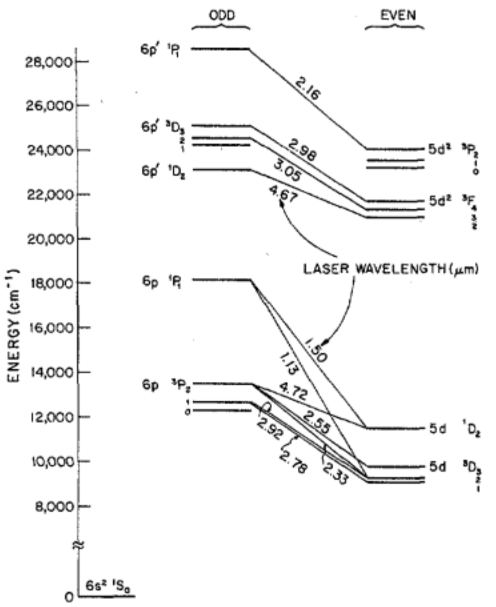

Fig. 1. Energy levels of observed laser lines in barium. The assignments of the two lines at 4.67 and 4.72 μm are less certain than the other nine assignments.

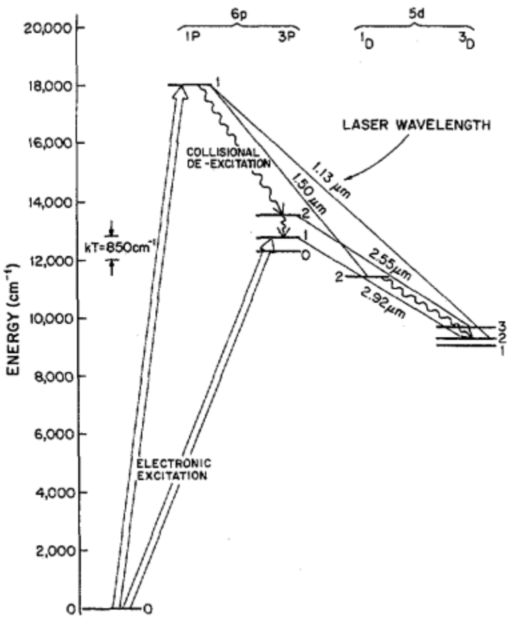

Fig. 2. Partial energy level diagram showing proposed electronic excitation and collisional deexcitation mechanisms.

TABLE I
OBSERVED LASER LINES IN Ba

λ	Identification	Wave Number (cm^{-1})	Optimal Press. Region	Reference
1.13	6p $^1P_1 \rightarrow$ 5d $^3D_2$	8844.746	Low	#3,4,5
1.50	6p $^1P_1 \rightarrow$ 5d $^1D_2$	6664.882	Low	#3,4,5
2.16	6p' $^1P_1 \rightarrow$ 5d^2 $^3P_2$	4635.317	Low	#4,5
2.33	6p $^3P_2 \rightarrow$ 5d $^3D_2$	4299.22	High	#4,5
2.55	6p $^3P_2 \rightarrow$ 5d $^3D_3$	3918.187	High	#4,5
*2.78	6p $^3P_1 \rightarrow$ 5d $^3D_1$	3602.631	Low	
2.92	6p $^3P_1 \rightarrow$ 5d $^3D_2$	3421.098	Low	#4,5
*2.98	6p' $^3D_3 \rightarrow$ 5d^2 $^3F_4$	3356.159	Low	#6
*3.05	6p' $^3D_2 \rightarrow$ 5d^2 $^3F_3$	3281.286	Low	#6
4.67	?6p' $^1D_2 \rightarrow$ 5d^2 $^3F_2$**	2140.376		#6
4.72	?6p' $^3P_2 \rightarrow$ 5d $^1D_2$**	2119.356		#4,5

*New laser transitions. The two lines at 2.98 μm and 3.05 μm were observed previously only in spontaneous emission.

**Two lines were observed at the wavelengths indicated, but the monochrometer resolution was insufficient to absolutely establish the levels of the transitions.

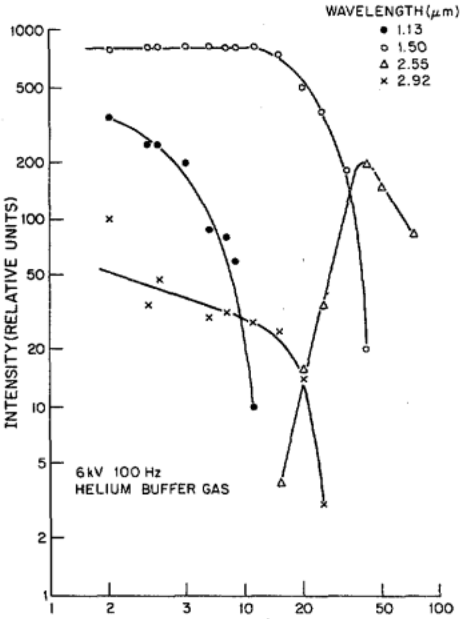

Fig. 3. Laser intensity variation in helium.

monochromator efficiency. The "kink" in the 2.92 μm output at 4 torr of helium may be an idiosyncracy of our particular laser cavity and is shown only as a tribute to its persistence.

The most striking feature of the pressure-dependence curves is that they have almost identical forms with both helium and neon as buffer gases, with the exception that the neon buffer gas pressure required to produce a given wavelength distribution is about a factor of three higher than the corresponding pressure for helium. This is a strong indication that this is a collisional effect, especially since the pressure ratio of three corresponds relatively closely to the ratio of the thermal velocities of the buffer gases. One would expect an He:Ne pressure ratio of 2.24 if the collisional processes scaled according to hard-sphere collision cross sections and depended only on the atomic diameter and velocity of the buffer gas.

Both the 2.55 and 2.33 μm (not shown) transitions oscillate only at high buffer gas pressure. The upper state of both lines is the $6p\ ^3P_2$ level which does not have an electronic transition to the ground state and, accordingly, is most probably not pumped directly by electron collisions. It is difficult to justify a collisional promotion of an atom in the $6p\ ^3P_1$ level to the $6p\ ^3P_2$ level because the latter is about 1 kT higher in energy. One may therefore conclude that the population of the $6p\ ^3P_2$ level comes from collisional deexcitation of the $6p\ ^1P_1$ level, the upper state of the two strongest lines at 1.13 and 1.50 μm.

Collisional coupling can also account for the pressure dependence of the 1.13, 1.50, and 2.92 μm transitions. Deexcitation of the $5d\ ^1D_2$ level to the $5d\ ^3D_2$ level will enhance the 1.50 μm transition at the expense of the 1.13 and 2.92 μm transitions leading to the persistence of the 1.50 μm line at relatively high pressure. One would also expect the 2.92 μm

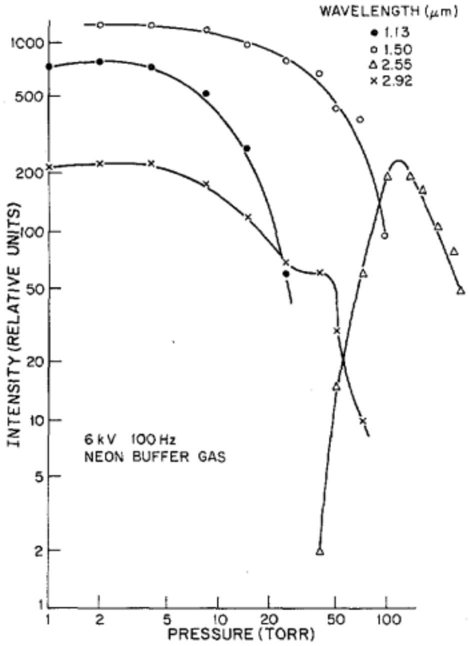

Fig. 4. Laser intensity variation in neon.

transition to lase at a higher pressure than the 1.13 μm transition because collisional relaxation of the $6p\ ^1P_1$ level to the $6p\ ^3P_1$ will inhibit the 1.13 μm line while benefiting the 2.92 μm line.

Collisional effects will be in evidence only if the rate of deexcitation is comparable to the inverse of the pulse length, τ_p. If the buffer gas means thermal velocity is v and the buffer gas number density is n, then the deexcitation cross section σ may be estimated from the relation

$$\sigma \approx (nv\tau_p)^{-1}.$$

The temperature and pulse length were approximately 950°C and 20 ns, respectively. The He number density at which the collisional deexcitation $6p\ ^1P_1 \rightarrow 6p\ ^3P_2$ occurs corresponds to a pressure of about 20 torr; at this pressure, the intensity of the 2.55 μm laser line originating from the $6p\ ^3P_2$ level has reached 10 percent of its maximum value. The resulting estimate of $\sigma_{\text{He-Ba}}$ is 1.3×10^{-15} cm^2. In a similar manner, we may associate the initial reduction of intensity of the 1.13 μm line with collisional population of its lower laser level via $5d\ ^1D_2 \rightarrow 5d\ ^3D_2$ deexcitation; this transition has decreased 10 percent in intensity at 8 torr He, yielding a cross section $\sigma_{\text{He-Ba}}$ of 2.5×10^{-15} cm^2. The gas kinetic He-Ba cross section is 4.2×10^{-15} cm^2; thus, our estimates of the two deexcitation cross sections correspond to $\frac{1}{3}$ and $\frac{3}{5}$ of the gas-kinetic cross section.

Collisional effects are clearly important, even for moderate-pressure operation of the barium laser, and with sufficient understanding of these processes, it may be possible to significantly improve the efficiency of this laser. Metal vapor lasers have great potential for high power and high efficiency, but it will be difficult to fully realize this potential without an increased understanding of the details of the collisional excitation and deexcitation mechanisms.

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Sealed-Off Continuous Wave Carbon Monoxide Laser at High Temperature Operation

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***Abstract*—The CO laser at 208-348 K operation is reported. Output power of 8.8 W, efficiency of 7.2 percent, and a lifetime of greater than 2500 h have been obtained. The laser lines were selected by a grating and showed oscillation on 63 lines in the 5.1109-5.9120 μm wavelength range were obtained. The strongest line had a power output of 1.4 W at room temperature and 1.11 W at 333 K operation. At 323 K there are 33 lines with a maximum power of 220 mW for one line.**

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FREED [1] first reported a CO laser operating at room temperature in 1971. Subsequently, this kind of laser was improved continually, and the lifetime of such lasers exceeded 4000 h which was reported by Smith [2] in 1977. Murray and Smith [3] reported a conversion efficiency of >15 percent and an output power per meter of active discharge length of >20 W. Nevertheless, no CO laser has been reported with an operation temperature of 308 K or higher.

A sealed-off room-temperature CW CO laser was operated in