

# The Amazing Cadmium Atom

William T. Silfvast, *Fellow, IEEE*

*Invited Paper*

**Abstract**—In this paper, I summarize the unique properties of the Cd atom that have led to many new types of laser excitation schemes and processes that began 35 years ago. These include the CW blue and ultraviolet laser transitions in  $\text{Cd}^+$ , the generation of 125-ps pulses (the shortest mode-locked pulses at that time), the process of Penning ionization as a laser excitation mechanism, recombination lasers produced by both laser-produced plasmas and a new segmented arc recombination laser (SPER laser) and the first soft-X-ray pumped photoionization laser, which are all described briefly herein.

**Index Terms**—Cadmium, cadmium lasers, metal vapor lasers, mode-locking, photoionization lasers, recombination lasers.

## I. INTRODUCTION

**L**ITTLE did I realize in March 1965, when I first observed a bright green flash of laser light from a Cd discharge tube [1], that it was the beginning of a very exciting journey, exploring the many different laser facets of the Cd atom. This was the first metal vapor laser that I discovered and just the beginning of my adventure with Cd. It would later lead me to the CW blue and uv laser transitions in  $\text{Cd}^+$ , the generation of 125-ps pulses (the shortest mode-locked pulses at that time), the process of Penning ionization as a laser excitation mechanism, recombination lasers produced by both laser-produced plasmas and a new segmented arc recombination laser (SPER laser), and the first soft-X-ray pumped photoionization laser; all resulting from this unique Cd atom! In this paper, I will describe the properties of the Cd atom that make it unique, and then I will briefly summarize how I was involved in the development of many of the different lasers that have resulted from this remarkable atom.

## II. UNIQUE PROPERTIES OF THE CADMIUM ATOM RELATING TO LASERS

### A. Cd Electronic Configuration

The Cd atom has an extremely interesting electronic configuration [2] from the standpoint of producing lasers. The ground electronic configuration consists of  $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^{10} 5s^2 \ ^1S_0$ . The active electrons associated with the energy levels and transitions we will be discussing are the outer (4d and 5s) electrons. Hence we will shorten the description of the Cd neutral ground state to  $4d^{10} 5s^2 \ ^1S_0$ .

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The author is with the School of Optics/CREOL, University of Central Florida, Orlando, FL 32816 USA.

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## Cadmium

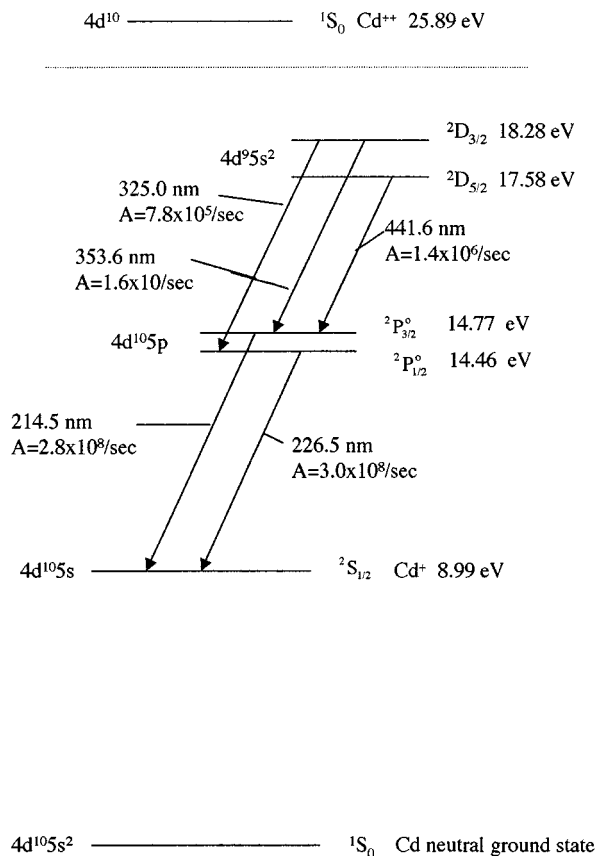


Fig. 1. Relevant energy levels of the Cd atom and single ion showing the inner-shell levels.

To ionize this atom (to produce Cd with one less electron) involves removing one of the 5s electrons to produce the  $\text{Cd}^+$  state of  $4d^{10} 5s \ ^2S_{1/2}$ . This requires an energy (ionization potential) of 8.99 eV as shown in Fig. 1. The removal of one electron without disturbing the other electrons has a much higher probability, by any number of processes including electron collisional ionization, Penning ionization, or photoionization, than processes that simultaneously affect two or more of the electrons.

In other words, for most atoms, to reach an excited state of the singly-ionized species starting from the neutral ground state, one electron must be removed and another electron changed. For example, to reach the first excited state of the  $\text{Cd}^+$  ion ( $4d^{10} 5p \ ^2P_{3/2,1/2}$ ), which splits into  $J = 3/2$  and  $1/2$  levels (see Fig. 1),

one of the 5s outer electrons must be removed and the other 5s electrons must be changed to a 5p electron. The probability of doing this is very much lower than the process of just removing one of the electrons. The removal of a single electron from any shell or subshell, other than the outer most subshell, generally involves an amount of energy greater than the ionization potential of the single ion, thereby leaving the atom in a doubly ionized state or higher. Such removal leads to Auger processes that are very familiar to X-ray spectroscopists.

The Cd atom differs from most other atoms in the following way. It turns out that the removal of one of the 4d electrons, instead of a 5s electron, only takes a small amount of additional energy (8.59–9.3 eV) above that necessary to remove the 5s electron. This additional energy is significantly less than the energy (16.9 eV) needed to remove a second 5s electron to produce doubly ionized Cd<sup>++</sup> in its ground state (4d<sup>10</sup> 1S<sub>0</sub>). Hence this inner shell electronic state 4d<sup>9</sup>5s<sup>2</sup>2D<sub>3/2,5/2</sub> is a stable state of the Cd single ion (see Fig. 1). In most other atoms, the energy required to remove an inner shell electron will lead to at least a double ionization process (or higher) via Auger decay. This unusual situation in Cd, therefore, distinguishes it from most other atoms. It allows for the existence of stable excited inner shell levels in the Cd ion that can be accessed from the Cd neutral atom ground state by affecting (removing) only one electron of the Cd basic electronic configuration.

### B. Radiative Properties of Cd Ion Levels

The unique inner shell stable states of the Cd ion also have interesting radiative characteristics as indicated in Fig. 1 where the relevant levels of the Cd<sup>+</sup> ion, the 4d<sup>9</sup>5s<sup>2</sup>, the 4d<sup>10</sup>5p, and the 4d<sup>10</sup>5s levels, are shown. The three laser transitions occurring from the 4d<sup>9</sup>5s<sup>2</sup> 2D<sub>3/2,5/2</sub> levels to the 4d<sup>10</sup>5p 2P<sub>3/1,1/2</sub> levels at 441.6 nm, 353.6 nm, and at 325.0 nm are indicated. The decay from the lower laser levels to the Cd<sup>+</sup> ground state can be seen to occur on far ultraviolet transitions. The transition probabilities of the transitions [3] are also shown in Fig. 1. One of the interesting features of the 2D levels is that the transition probabilities from those levels to the 2P levels (the laser transitions) are much lower than would be expected for a normal allowed electric dipole transition. The oscillator strengths of these transitions are approximately 0.0068, 0.0003, and 0.0037 for the 441.6-, 353.6-, and 325.0-nm transitions, respectively. Hence, the slow radiative decay of these levels and the very fast decay of the lower laser levels to the ion ground state easily establish the population inversions for these CW lasers. This low oscillator strength is due to the fact that the transitions from 4d<sup>9</sup>5s<sup>2</sup> to 4d<sup>10</sup>5p involve the change of two electrons rather than the usual change of only one electron, as is the case for most electric dipole allowed transitions.

The decay processes mentioned above are relatively unique to the Cd ion. The only other atom that has similar properties is the Zn ion, which I have also made to lase, but the Zn transitions from the 3d<sup>9</sup>4s<sup>2</sup> 2D levels are in the far red portion of the spectrum and consequently are not as unique as the blue and ultraviolet Cd laser transitions. Zn also has a much lower Penning ionization cross section from He metastables making it not as conducive to producing CW lasers. Interestingly enough, the

equivalent 5d<sup>9</sup>6s<sup>2</sup> 2D levels in mercury (Hg) are lower lying than the 5d<sup>10</sup>6p 2P levels and hence there is no allowed radiative decay from these excited 2D levels of the Hg ion.

### C. Penning Ionization as an Excitation Process to Excited Ion Levels

When any neutral atoms other than Ne are in proximity to He metastable atoms, such as in a gas discharge, there is a high probability that collisions between the two types of atoms will occur that will transfer the He metastable energy to the neutral atoms, thereby ionizing them. In order to conserve energy in this binary collision process, the energy difference between the ionization potential of the neutral atom and the He metastable levels is taken up by the electron ejected from the neutral atom in the ionization process. In most atoms this transfer of energy occurs with the highest probability to the ion ground state of the neutral atom. Transfer to excited states is much less likely, because it would involve changing two electrons of the species, thereby negating the possibility of using this as a laser excitation mechanism for that species.

In Cd, the situation is different. Since only a single electron has to be removed for a neutral Cd atom to be excited from the neutral ground state to the inner-shell 2D excited levels, the Penning ionization cross section is much higher to populate these two levels than other excited energy levels of the Cd ion, and is almost as high as that to populate the Cd ion ground state [4]. For example, the cross section to the ion ground state (4d<sup>10</sup>5s 1S<sub>0</sub>) is  $2.6 \times 10^{-15} \text{ cm}^2$ , to the upper laser levels (4d<sup>9</sup>5s<sup>2</sup> 2D) it is  $1.3 \times 10^{-15} \text{ cm}^2$  and to the lower laser levels (4d<sup>10</sup>5p 2P) it is  $0.5 \times 10^{-15} \text{ cm}^2$ . Penning ionization cross sections to other excited levels of Cd<sup>+</sup> are significantly lower. The two He metastable levels are shown in Fig. 2 along with the relevant Cd levels. The excess energy taken up by the ejected electrons in the Penning process is of the order of 1.5–3 eV when transferring to the 2D states and 10.5–11.8 eV to the Cd<sup>+</sup> ground state.

### D. Photoionization Cross Section

The unique electronic configuration of Cd allows for another interesting excitation process to excite the 4d<sup>9</sup>5s<sup>2</sup> 2D levels of the Cd ion. The process is photoionization using radiation flux in the 10–70 nm wavelength region. The photoionization cross section for neutral Cd atoms in their ground state [5], [30] is shown in Fig. 3. Any photon with an energy higher than approximately 12 eV but less than 125 eV will be absorbed by the Cd neutral atom, placing it predominantly in the excited Cd ion 4d<sup>9</sup>5s<sup>2</sup> 2D state. The maximum photoionization cross section for this process is 14 Mb, occurring at a wavelength of approximately 30 nm (41 eV). The cross section to produce Cd ions in the Cd ion ground state by this same photoionization process is more than one order of magnitude lower [5], [30] and occurs only over a much smaller energy range (9–12 eV). Hence the process of photoionization to the 2D states of the Cd is by far the most likely process for photon absorption of Cd vapor in the EUV-soft-X-ray wavelength region. This will be later shown to allow the generation of interesting photo-ionization-pumped lasers.

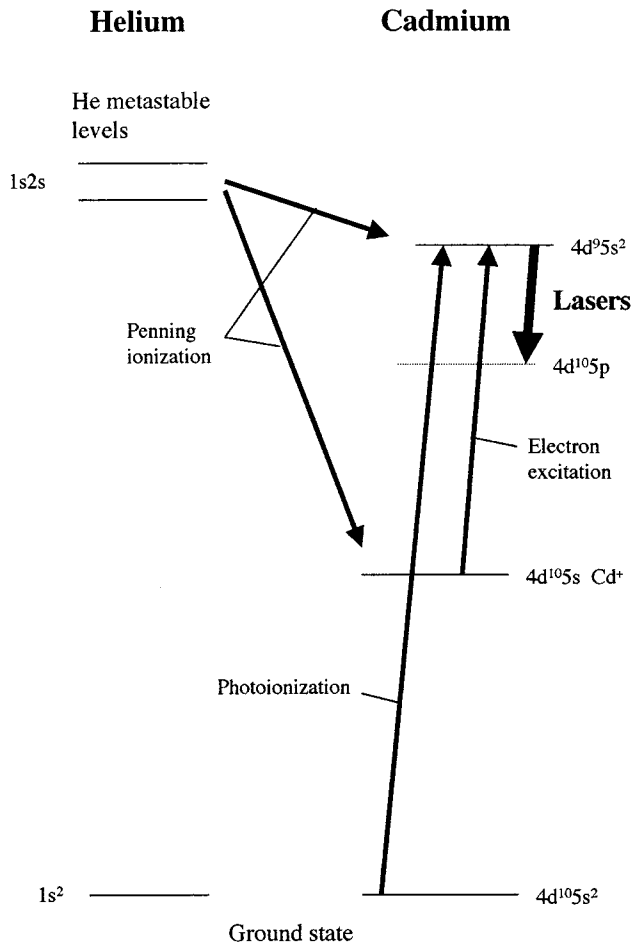


Fig. 2. Excitation pathways to the relevant levels associated with the blue and uv lasers in the Cd ion.

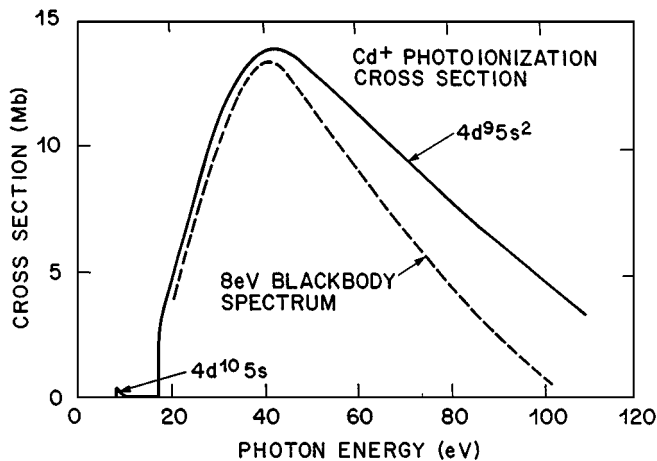


Fig. 3. Photoionization cross section for removing either a 4d or a 5s electron from the neutral Cd atom superimposed with an 8 eV blackbody spectrum.

### E. Vapor Pressure

The Cd vapor pressure is relatively high [6], producing approximately one torr of vapor at a temperature of 320 °C. This allows a Cd laser to be operated in a glass enclosed structure, as opposed to quartz or high temperature ceramics that are needed for other high temperature lasers.

### F. Cataphoresis Effect in a CW Discharge

Normally a uniform vapor is obtained within a chamber by placing the vapor source (either liquid or solid) within the chamber and heating the entire chamber uniformly. In the case of Cd, the chamber would have to be heated to a temperature of approximately 260 °C to operate the He–Cd CW laser at optimum Cd density; however such an arrangement would be very impractical. The only region that must be heated is the region of the discharge capillary bore where the excitation and amplification occur. It is much more desirable to have the laser windows, mirror, electrodes, etc. at or near room temperature. This is achieved by using a process known as cataphoresis [7] to control the Cd vapor distribution. In this process the Cd metal is heated and vaporized at the anode (positive potential) end of the discharge and is transported toward the cathode end (negative potential) of the discharge by the electric field acting upon the Cd ions that are produced by the discharge current. The Cd atoms then condense in the cathode region. The laser species is essentially “flowing” down the capillary, albeit at a very slow rate of approximately one to two grams per 5000 h.

This cataphoresis process is sensitive to the fractional degree of ionization of the desired atomic species [7] (such as Cd) to be transported through the discharge region. A fractional ionization of the order of 1% is required to produce the uniform distribution throughout the entire length of a long discharge capillary such as that used in the He–Cd laser. In the case of Cd, this unusually high fractional ionization is produced primarily due to the process of Penning ionization, as mentioned above as one of the excitation processes. As explained above, the highest Penning ionization cross section to produce a specific Cd<sup>+</sup> level is to produce the ion ground state ( $4d^{10}5s\ ^2S_{1/2}$ ). Hence the Penning ionization process plays a major role in producing the high degree of ionization that provides the uniform vapor distribution along the gain region of the capillary bore.

### G. Isotope Shift Relating to Laser Bandwidth in the He–Cd Laser

Different isotopic forms of the same element exist in various relative abundances when the element is obtained in its naturally occurring form. These different isotopes consist of atoms having the same number of protons and electrons, which identifies them as belonging to the same element, but having different numbers of neutrons. Naturally occurring quantities of various elements contain certain specific fractions of various isotopes. For example, Ne exists naturally as 90.8% Ne<sub>20</sub> (10 neutrons), 0.26% Ne<sub>21</sub> (11 neutrons), and 8.9% Ne<sub>22</sub> (12 neutrons).

Having slightly different numbers of neutrons within the nucleus produces small differences in the values of the energy levels of atoms. Such energy shifts cause a slight difference in center frequency of the emission lines for the different isotopes. In most cases these different values of energy are too small to be noticed from the standpoint of the emission linewidth in a laser medium. However, in the case of the CW Cd laser transitions, the isotope shift in the emission spectrum between different isotopes is very significant.

In general there are two causes for the isotope shifts [8] which result in frequency shifts of the emission. The one predominant

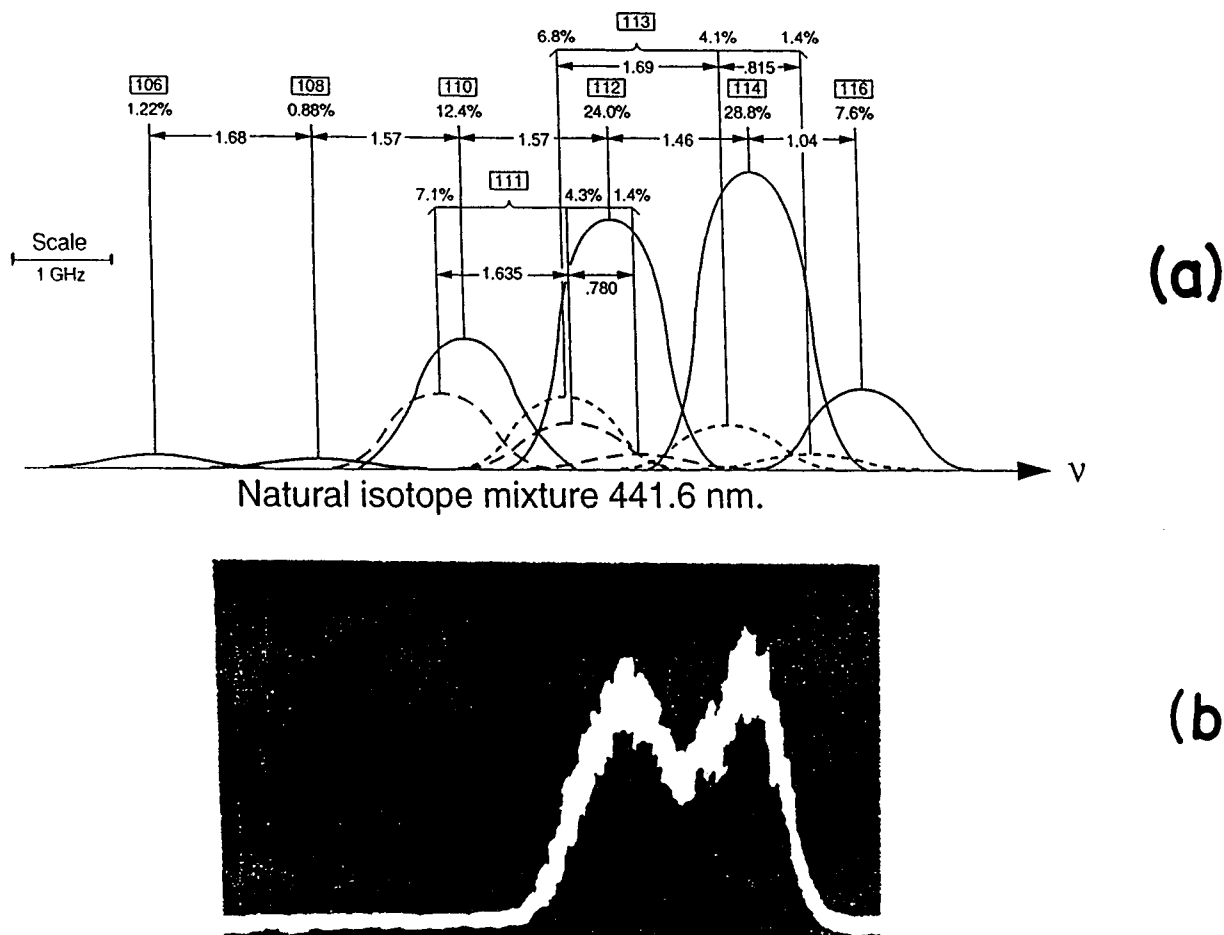


Fig. 4. A diagram showing the emission spectrum of the 441.6-nm transition in the Cd ion for a naturally occurring mixture of Cd isotopes.

for the CW Cd laser transitions is a volume shift produced by a difference in volume of the nucleus for the Cd atoms with different numbers of neutrons. The magnitude of this volume shift generally depends upon the specific electronic configuration of the energy levels involved in the transition. Appreciable shifts are observed only when the number of *s* electrons differs between the upper and lower levels of the transition, as is the case with these Cd transitions. This shift leads to a higher frequency of the emission for the heavier isotopes. The even isotopes produce approximately equal shifts, whereas the odd isotopes split into several levels making their emission spectrum slightly more complicated.

The naturally occurring isotope distribution for the 441.6-nm emission line in Cd is shown in Fig. 4(a) with transitions associated with individual isotopes ranging from Cd<sub>106</sub> to Cd<sub>116</sub>. The relative abundance of each isotope is shown along with the isotope shifts between adjacent isotopes. The total emission spectrum at 441.6 nm for a gas discharge involving a naturally occurring mixture of cadmium would then comprise the sum of all the individual emission spectra of each isotope as shown in the figure. The two isotopes with the most abundance are Cd<sub>112</sub> and Cd<sub>114</sub>.

I should emphasize at this point that all the above discussed effects (except vapor pressure) are related to the unique electronic configuration of the Cd atom!

### III. CW He–Cd LASER

After observing the green Cd laser transitions in 1965 [1] and later the 441.6-nm laser emission in Cd in 1966 [9], I left the University of Utah and went to the Clarendon Laboratory at Oxford on a NATO Postdoctoral Fellowship to work with John Sanders. During that time I was involved in making high gain measurements in the pulsed lead vapor laser with John Deech [10], who was pursuing his D.Phil. degree at the time. While I was there, Grant Fowles and graduate student Bruce Hopkins continued to investigate the Cd laser. When I returned to the States in 1967 Fowles informed me that they had seen quasi-CW laser action on the 441.6-nm laser transition when operating the laser with a 120-Hz neon sign transformer [11]. The laser output occurred over an extended duration of several hundred microseconds at the peak of each current cycle. This result excited me, and I decided to pursue this laser further when I began working at Bell Labs in August 1967. I demonstrated CW laser action [12] in early 1968, observed the 325.0-nm laser transition [13] in 1969, and developed a compact version of the laser [14] in 1971. Around that time, people in one of the development areas of Bell Labs were attempting to develop a “remote blackboard system” that had a need for a compact ultraviolet laser. The 325 nm laser seemed to be appropriate for this system. As a result, I became involved in seeking an outside supplier

for these lasers. One of the companies we approached was Coherent, Inc. Mark Dowley was given the project at Coherent and soon thereafter he left Coherent and started LiCONix, Inc. to produce He–Cd lasers. The rest is history as far as the He–Cd laser is concerned.<sup>1</sup>

As the development of this laser has evolved, there are now typically two versions of the laser including a long discharge tube with a bore length (gain region) of the order of 60–75 cm, and a shorter version with a bore length of the order of 25–35 cm. The longer version is comprised of either one long bore or two shorter bores within the same laser cavity. The lasers, including their air-cooled housings, have lateral dimensions of the order of 15 mm, are approximately 40 cm longer than the bore length, and have a separate small power supply. The larger lasers produce up to 200-mW multimode at 441.6-nm and 100-mW multimode at 325 nm. A 10-mW single TEM<sub>00</sub> mode blue laser is also produced from a 25–30-cm bore length. A heated Cd reservoir is located at the anode end of the laser discharge bore region. A metal vapor trap is located beyond the cathode to prevent metal vapor from condensing on the laser window or mirror. As the Cd vapor condenses at the cathode end of the laser tube, it traps He atoms within the Cd metal matrix, thereby gradually reducing the He pressure within the operating region. Therefore, at the cathode end of the tube, a ballast (large reservoir) is installed to provide an additional supply of He gas to help maintain the proper He pressure. To provide an additional He supply there is another separate reservoir containing He at or near atmospheric pressure located beyond the ballast. The He in that reservoir is diffused through a membrane into the ballast region as needed to maintain the proper He pressure. The diffusion membrane is temperature sensitive and the diffusion rate is electronically controlled to maintain the proper pressure within the discharge region of the tube. A rigid cavity structure is used to maintain the mirror alignment with respect to the fixed location of the laser bore.

Because of the cost involved for single isotopes of Cd, most commercial He–Cd lasers use the naturally occurring mixture. The Cd<sub>112</sub> and Cd<sub>114</sub> isotopes have the greatest percentage contribution in the natural mixture of Cd and are, therefore, the primary contributors to the laser output, as shown in Fig. 4(b). A single isotopic species of cadmium will produce the narrowest laser emission spectrum which is determined by the Doppler width or approximately 1.5 GHz, thereby providing the highest laser gain and also the highest power output on both the blue and uv transitions.

#### IV. EXCITATION MECHANISM OF THE CW He–Cd LASER

Shortly after obtaining CW laser action at 441.6 nm, I became very interested in determining the excitation mechanism of the He–Cd laser. Colin Webb, who was then at Bell Labs, Murray Hill, NJ and is now at the Clarendon Lab, Oxford, U.K., acquainted me with the Penning ionization mechanism in gas collisions. I found a measurement of the Penning cross section

involving transfer of energy from He metastable atoms to the Cd ion [4]. The cross section was high enough that the Penning process appeared possible for the Cd laser. Consequently I began to make measurements of He metastable densities in a dc discharge. At that time I obtained a voluminous amount of data for a range of parameters but somehow never got around to publishing them. The results for a discharge current of approximately 50 mA in a 4-mm bore discharge tube in pure He at a few torr pressure included a triplet metastable density of approximately  $2 \times 10^{12}/\text{cm}^3$  and a singlet metastable density that was nearly a factor of 10 lower. These densities were several orders of magnitude higher than typical excited state densities of most atoms and ions when operated under similar conditions. Hence, such a source of stored energy appeared to offer a very good chance of being the mechanism for the He–Cd laser.

I had been impressed with the paper by Gordon, *et al.* [15] when they showed that the He–Ne laser was populated by collisions with He metastable atoms. In their experiments, they varied the discharge current and showed that the Ne upper laser level followed the population of the He singlet metastable atoms. I could not do a similar experiment since I could not easily control the Cd density when the current was varied. So I decided instead to track the product of the He metastable density and the neutral Cd density as I varied the Cd density (temperature) in the discharge at a very low but constant current. This density product should be proportional to the emission from the upper laser level if Penning ionization were the dominant excitation mechanism. I had to carry out this experiment at a low discharge current so as not to alter the Cd density due to cataphoresis. For these conditions, I demonstrated that Penning ionization was the dominant excitation process for the 441.6-nm He–Cd laser transition [16].

Over the years a controversy has developed over the excitation mechanism for this laser. Presently there are three excitation mechanisms (Fig. 2) that have been proposed for the excitation of the He–Cd laser. The first one is Penning ionization from He metastable levels to the Cd upper laser levels as I had demonstrated in a low current He–Cd discharge [15]. The second process is electron excitation from the Cd ion ground state to the upper laser level proposed by Goto [17], which he claimed became dominant at higher currents. The third process I also proposed is a minor contributor since it can be shown to represent only 3–5% of the total excitation for the conditions of the He–Cd laser discharge. This process involves photoionization of the Cd atoms to populate the upper laser levels [18] via emission from the 50–60-nm transitions of the excited He atoms radiating within the volume of the discharge. Goto published several papers supporting his claim, but a more recent paper has appeared that supports Penning ionization [19]. This is not an easy problem to resolve, although I think Penning ionization has more evidence in its favor.

#### V. MODE LOCKING OF THE He–Cd LASER

In the early seventies, Peter Smith was doing mode-locking studies of the He–Ne laser [20]. I realized at that time that if we were to obtain a special mixture of Cd isotopes, we could generate much shorter pulses with the He–Cd laser than one

<sup>1</sup>At that time both Spectra-Physics and RCA were selling much larger versions of the He–Cd blue laser but those were soon discontinued but LiCONix continued to prosper and at this writing is still one of the two commercial manufacturers of He–Cd lasers.

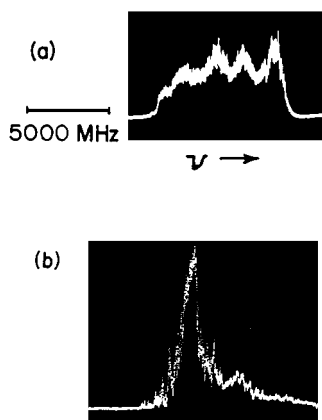


Fig. 5. (a) Completely mode-locked spectrum of the 441.6-nm Cd laser for a special uniform isotope mixture of Cd. (b) 150-ps mode-locked pulse trace (200 ps/div) generated when the fully mode-locked bandwidth of Fig. 5(a) was achieved.

could obtain with the He–Ne laser due to the much wider potential gain bandwidth. Peter expressed an interest in collaborating with me on this experiment so I obtained a special Cd isotope mixture that involved equal amounts of the even isotopes of Cd ranging from 106 to 116. With a laser Doppler width for each isotope of 1.5 GHz and the isotope shifts of adjacent even isotopes that are approximately equal to the Doppler width, a full laser gain bandwidth of 8 GHz appeared to be possible. Mode-locking the laser with this special isotope mixture suggested the possibility of obtaining pulses approaching 100 ps in duration, which would have been the shortest mode-locked pulses yet generated at that time. The expense of mixing equal amounts of the even isotopes was precluded by adding portions of the lower percentage even isotopes to the naturally occurring mixture.

For these experiments, a 3.5-mm bore by 2-m-long discharge tube was used. The Cd was enclosed in a heated side-arm at the anode end of the discharge and was cataphoretically pumped to the cathode end to provide a uniform vapor distribution within the laser bore. The discharge tube was operated at a current of 140 mA at an optimum He pressure of 3.5 torr. A quartz acousto-optic modulator was inserted in the cavity at the Brewster angle near one of the laser mirrors. The mode-locked pulses were detected with a high-frequency photodiode and displayed on a sampling oscilloscope. The estimated response time of the system was 50 ps. The output was also fed into an interferometer to obtain the frequency response of the mode-locked system.

The experimental results [21] of the full mode-locked bandwidth are shown in Fig. 5(a) and the time-dependence of the narrowest pulse is shown in Fig. 5(b). Only when the bandwidth display indicated complete mode-locking, as in Fig. 5(a), were the narrowest pulses observed. At that time, these were the shortest mode-locked pulses yet obtained from a laser.

## VI. RECOMBINATION LASERS IN Cd

Obert Wood and I became interested in trying to make a short wavelength laser in both the VUV and EUV spectral regions. We had already been experimenting with laser-produced

plasmas and had made the first laser in several noble gases initiated within plasmas of those gases. But we thought that vaporizing a solid species with a focused laser (rather than attempting to ionize a gas with a focused laser) and having that resulting plasma expand and cool, would offer the easiest route to success. We were attracted to the concept of collisional recombination as a pumping mechanism because, in principle, essentially all of the ions that were produced by the focused laser would recombine to the next lower ionization stage and would then move downward rapidly from one level to the next lower lying level by collisions with the free electrons provided by the plasma. Eventually, the bound electron reaches a level below which there is a significant energy gap. Above that gap, collisional decay would dominate. Below that gap, radiative decay would dominate because the large energy gap would very significantly reduce the collisional decay rate. Hence, in principle, almost all of the decaying electrons would arrive at this level above the gap and contribute to laser output, making such a laser potentially very efficient. Our approach was to begin by making lasers in the near infrared (in neutral atoms), in the visible (in single ions), and in the ultraviolet (in double ions). These wavelength regions are typical for different ionization stages due to the increase in binding energy of each successive ion stage. Our plan was to attempt to scale the results obtained at low ionization stages to higher ion stages and thus produce shorter wavelength lasers, hopefully extending this to the soft-X-ray spectral region. We were never successful in implementing that plan but we did produce quite a number of interesting new lasers in the infrared, visible, and ultraviolet portions of the spectrum as discussed below.

### A. Cd Recombination Lasers in Laser-Produced Plasmas

The first lasers we developed by vaporizing solid targets with a laser-produced plasma [22] were in Cd. Three laser transitions were observed in the neutral spectrum at 1.43, 1.45, and 1.64  $\mu\text{m}$ . These lasers were produced by focusing either a Nd:YAG laser or a CO<sub>2</sub> laser onto a Cd metal target, thereby producing a Cd plasma consisting primarily of Cd<sup>+</sup> ions and electrons. The Cd plasma was allowed to expand into a background gas which served to retard and cool the plasma. Rapid cooling is important to significantly increase the recombination rate and thereby more rapidly pump the upper laser level via collisional recombination and subsequent collisional decay to the upper laser level [23].

### B. Segmented Arc Cd Recombination Lasers (SPER Lasers)

After our success in generating a laser-produced plasma recombination laser in Cd vapor, I began thinking about how metal vapor arcs can be produced between two closely spaced metal electrodes when a voltage is applied across the electrodes. I thought we might be able to take advantage of this in producing a recombination laser. We placed a series of 10 mm  $\times$  2 mm  $\times$  1 mm Cd metal strips along a 15-cm-long glass plate, each separated by approximately 1 mm from the next, using double-sided masking tape to hold the strips to the plate. We placed this arrangement inside a glass chamber that served as a vacuum vessel. We applied a pulsed voltage across the length of the strip and were able to generate



that cross section in Cd and the shape of an 8 eV blackbody emission spectrum (Fig. 3). Since laser-produced plasmas could be approximated as blackbody sources, I used the blackbody spectrum to model the photoionization pumping of the  $4d^95s^2$  state of  $Cd^+$  with a laser-produced plasma. The model indicated extremely high gain on both the 441.6 nm and 325.0 nm transitions, of the order of  $5\text{ cm}^{-1}$ . When I returned to Bell Labs for a week in the spring of 1983, John Macklin, Obert Wood, and I set up the experiment using a Cd heat pipe containing a rotating Ta target on which a Nd:YAG laser was focused to produce a pumping plasma source.

With approximately 1 torr of Cd vapor in the heat pipe, we fired the laser onto the Ta target and observed a very strong spike of emission at 441.6 nm [18] on the very first shot! The soft-X-rays from the laser-produced plasma pumped the surrounding Cd atoms directly to the upper laser levels, with essentially no direct pumping to the lower laser levels (Fig. 2). This was one of those few cases where I had done the theory and then had the experiment work the very first time. The measured gain agreed quite well with the theory [18], and we were off and running. We and others developed several new lasers using this pumping technique over the next few years [27], but we were unable to extend it to ultra-short wavelengths. Roger Falcone and his colleagues and students at Berkeley and Lawrence Livermore National Laboratory were later able to pump xenon [28], using the same inner shell d-electron pumping technique, to produce laser action in  $Xe^{2+}$  at 108.9 nm after Auger decay of the inner-shell excited  $Xe^+$  ion. This is the more typical inner-shell excitation process in which the resulting excited level is unstable and rapidly decays by autoionization.

### VIII. AFTERTHOUGHT

I have not worked with Cd since I left Bell Labs in December 1989. However, writing this paper has brought back many fond memories. Perhaps it is time to investigate the properties of Cd in the EUV spectral region, an area in which I am now involved, to develop an intense EUV source for the microlithography industry [29], [31]. Perhaps Cd is in my blood. But, on second thought, that might not be a particularly healthy situation.

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William T. Silfvast (M'85–SM'86–F'90), photograph and biography not available at time of publication.