RICE UNIVERSITY

THE HELIUM VACUUM-ULTRAVIOLET LASER

by

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Abstract

The emission spectrum of electron bombarded liquid helium has a broad continuum centered around 800 Å, which is believed to originate in the $A'\Sigma^+ \rightarrow X'\Sigma^+$ transition in He$_2$. This system has been studied as a possible medium for a vacuum-ultraviolet laser. It was found that dense helium gas would be better for such a laser. A transversely excited laser was built and tested on nitrogen and hydrogen before trying helium at ten atmospheres pressure. Lasing was observed with nitrogen, but it was never confirmed in the other two gases. Possible causes of failure are discussed along with several suggested improvements in the system. Finally, the feasibility of a pulsed-electron-accelerator powered laser is considered.
ACKNOWLEDGEMENTS

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Dr. Everett D. Stokes
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This thesis is dedicated to my mother and father.
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CHAPTER I

INTRODUCTION

Much progress has been made in recent years in expanding the range of frequencies attainable with lasers. Today, with the advent of tuneable dye lasers, one can construct a laser to produce virtually any desired wavelength from 12,000 Å to 3400 Å. However, lasing becomes more difficult to achieve as the wavelength decreases. The frequencies of existing lasers can often be doubled, tripled, or raised to even higher harmonics through the use of special optical techniques with nonlinear dielectrics. Unfortunately, the process is rather inefficient and is only applicable to lasers with large power outputs. A further limitation arises from the fact that optical materials are opaque to light of very short wavelengths.

Several non-tuneable lasing transitions have been used to extend lasing beyond the range of frequency multiplication processes. Carbon monoxide has been found to lase at wavelengths as short as 1810 Å, while a liquid xenon laser has produced a line at 1760 Å. The Lyman bands of molecular hydrogen have been made to lase at several wavelengths near 1600 Å. Lasing has also been observed at 1600 Å in gaseous xenon from the transition

\[ \text{Xe}_2^* \rightarrow \text{Xe}_2 + h\nu. \]
A laser using the Werner bands of H$_2$ holds the present record for the shortest wavelength, with a line reported at 1161 Å.

Recent investigations of the ultraviolet emission spectrum of electron bombarded liquid helium suggest that it might make a suitable medium for a laser operating at 800 Å. Using 160-keV electrons to excite the helium, it was found that roughly 10% of the incident energy was emitted as ultraviolet light. Most of the light was concentrated in a broad continuum with a maximum near 800 Å, as shown in Figure 1.

The source of this continuum is believed to be transitions of the He$_2$ molecule from the first excited state ($A'\Sigma^+$) to the ground state ($X'\Sigma_g^+$). The potential curves of these two states are reproduced in Figure 2. Since the ground state potential curve is repulsive, the molecule dissociates after the radiative transition. As will be seen, this is a favorable circumstance, in that there will be no population buildup in the ground state. This makes it easier to produce the large excess population of the excited state which is necessary for lasing to take place.
CHAPTER II

LASER THEORY

A. Laser threshold conditions.

The first requirement for a laser is a system with at least two energy levels, the higher one of which can be made to be more highly populated than the lower. Transitions can take place from the upper to the lower level by the emission of a photon. If this photon then collides with another particle in the upper level, the particle may be stimulated to emit a similar photon with the same energy, direction, and phase as the first photon. These two photons can then stimulate further emissions, and a laser pulse is built up. However, should the photon collide with a particle in the lower level, the probability of its being absorbed is the same as the probability of stimulated emission was in the previous case. Thus, in order to produce a net amplification of the photon flux, there must be a greater population of particles in the upper level than in the lower one. Such a condition is known as a population inversion.

An indication of the amount of inversion required can be arrived at by assuming that, for lasing to occur, each photon must stimulate the emission of at least one other photon before leaving the laser cavity. The probability
of a stimulated emission is equal to the excess density of excited particles times the length of the photon path multiplied by the cross section for stimulated emission. To produce any amplification of the light pulse, this probability must be greater than or equal to one.

Many lasers have mirrors on each end of the cavity which reflect most of the laser pulse back through the lasing medium in order to increase the photon path length. If the length of the cavity is \( L \), and the reflectivity of the mirrors is \( R \), the total path length will be

\[
L(1+R+R^2+\cdots) = \frac{L}{1-R}.
\]

The cross section for a resonant transition is \( \lambda^2/8\pi \), where \( \lambda \) is the wavelength of the photon. Since the emission spectrum lines have finite widths, an additional correction term \( \Delta \nu_n/\Delta \nu_{\text{exp}} \) should be included, where \( \Delta \nu_n \) is the frequency spread due to the natural lifetime of the excited state, and \( \Delta \nu_{\text{exp}} \) is the actual experimental frequency spread of the emitted photons.

The conditions required for laser action are thus

\[
1 \leq (N_u-N_\downarrow)L(\Delta \nu_n/\lambda^2)/(1-R)(\Delta \nu_{\text{exp}}/\lambda^2),
\]

where \( N_u \) and \( N_\downarrow \) are the number densities of particles in the upper and lower states respectively. This equation can be expressed in a more convenient form by noting that

\[
\Delta \nu_{\text{exp}} = c(1/\lambda_2 - 1/\lambda_1) = c(\lambda_1-\lambda_2)/(\lambda_1\lambda_2) \approx c(\Delta \lambda_{\text{exp}})/\lambda^2,
\]

where \( c \) is the speed of light, and \( \lambda_1 \) and \( \lambda_2 \) are the maximum and minimum wavelengths of the emission line at half
its maximum intensity. For $\Delta \nu_n$ one can use $1/\tau_n$, where $\tau_n$ is the natural lifetime of the upper level. The minimum amount of inversion required for lasing is therefore

$$\Delta N_{\text{th}} = N_u - N_l = 8 \pi c (\Delta \lambda_{\text{exp}}) \tau_n (1-R)/\lambda^4 L.$$  

To make it easier to achieve the threshold conditions, $\Delta N_{\text{th}}$ should be kept as small as possible. Thus the most desirable parameters for a system are a narrow emission line with a short natural lifetime and a long wavelength. The cavity should be long and have highly reflecting mirrors.

B. Suitability of the liquid helium system.

As was noted earlier, the ground state of $\text{He}_2$ is dissociative. The population of the lower state will be essentially zero, and $\Delta N$ is just the density of $\text{He}_2$ molecules in the $A'\Sigma^+$ state. The natural lifetime of this state is about $10^{-8}$ seconds.\(^{10}\) The wavelength of the emitted light is centered around 800 $\text{Å}$, with a full width at half maximum of about 170 $\text{Å}$.\(^9\) One problem at such short wavelengths is that mirrors are very inefficient. The laser must thus be operated without mirrors in what is known as the super-radiant mode. Using the above parameters, one finds that a number density of $3 \times 10^{18} / \text{L cm}^{-3}$ $\text{He}_2$ molecules in the $A'\Sigma^+$ state is needed to produce lasing.

It is useful at this point to look at the power requirements. A typical electron accelerator might produce 160-keV electrons with a beam width of 1 cm. Such a beam penetrates
to a depth of about 0.3 cm into liquid helium. The length of the excitation region is thus 1 cm, and its volume is approximately 0.3 cm³. The threshold value of ΔN for a laser cavity of such size is 3×10⁻¹⁸ cm⁻³. A 1-mA beam of 160-keV electrons has a power output of 10²¹ eV/sec. If ten percent of this power is radiated as ultraviolet light, then about 10²⁰ eV/sec comes from the transition $A'\Sigma_u^+ \rightarrow X'\Sigma_g^+$. Each photon has an energy of 15 eV. This means that 6×10¹⁸ transitions per second would occur by spontaneous emission. Using the natural lifetime of 10⁻⁸ seconds, the density of $A'\Sigma_u^+$ states would be

$$\frac{(6×10^{18} \text{ sec}^{-1})(10^{-8} \text{ sec})}{(0.3 \text{ cm}^3)} = 2×10^{11} \text{ cm}^{-3}$$

to sustain such an emission rate. Since the density needed for threshold is 10⁷ times larger than this, it would require a current of 10⁴ A to achieve threshold conditions. Currents of such magnitude are unobtainable on a continuous basis, and even if available, such a current would certainly cause localized boiling in the liquid helium. Excitation of liquid helium by an electron accelerator would thus appear to be ruled out as a means of achieving lasing. However, a high current, pulsed electron accelerator has some possible applications, as will be discussed in Chapter 6.

During the past few years techniques have been developed for operating transversely excited gas lasers at
atmospheric pressure or above. Large input power levels are possible in such a system. Since the emission spectrums of liquid helium and high-pressure gaseous helium have been shown to be similar, attention was focused on the possibility of using dense helium gas rather than liquid helium for the lasing medium.

C. Requirements of the dense helium gas system.

A typical transversely excited gas laser consists of a long tube with a row of electrodes running down each side. When a voltage pulse is applied across the electrodes, an electrical discharge takes place within the tube which excites and ionizes some of the gas contained therein. If the power input is large enough to produce a population inversion, lasing may result.

The reactions leading to the formation of the $A^1\Sigma^+$ state of He$_2$ are not fully understood. However, an attempt will be made to summarize the most likely processes along with their rates of reaction.

When the laser is fired, the first products created by electron impact are excited helium atoms, singly ionized helium atoms, and electrons. Initially the laser will thus contain He, He$^*$, He$^+$, and e$^-$. The electrons used to excite the gas have such large energies that one would expect many more ions to be formed than excited atoms. For that reason, even though they do make some contribution to the
overall reaction scheme, the excited atoms are believed to be of little importance for the purpose at hand. The three reactions of particular interest are shown in Table 1. A list of other known reactions which seem to be of secondary significance is given in Table 2.

The reactions involving He$^+$ have little effect at pressures above 5 torr due to the rapid conversion of the He$^+$ to He$_2^+$.\(^\text{14}\) It has also been shown that the dissociative recombination of He$_2^+$ makes a negligible contribution to the total electron recombination rate.\(^\text{15}\) It is believed that in room temperature helium afterglows with pressures greater than one torr, the ion primarily responsible for electron recombination is the He$_3^+$ ion.\(^\text{16}\) There are several other reaction schemes shown which also lead to the production of He$_2^*$. These will only serve to increase the total reaction rate, however, and need not be considered for the present order-of-magnitude calculation.

The primary concern is whether the three reactions given in Table 1 can take place in less than $10^{-8}$ seconds, the lifetime of the A'$\Sigma^+$ state of He$_2$. The first reaction has a time constant of $(k_1 N_{He}^2)^{-1}$. $N_{He}$ is the density of helium atoms, or about $3.2 \times 10^{16}$ p cm$^{-3}$, where p is the pressure given in torr. The time constant is thus $9.2 \times 10^{-3}/p^2$ seconds. It would require a pressure of almost 1000 torr to make this less than $10^{-8}$ sec. The second reaction has been shown to proceed faster than the first,\(^\text{17}\) so at high
pressures it too will certainly be rapid enough.

The third reaction has a time constant of \((k_3 N_e)^{-1}\), where \(N_e\) is the free electron density. In order to have a time constant of \(10^{-8}\) seconds, \(N_e\) must be \(1.4 \times 10^{14} \text{ cm}^{-3}\). Such a density should be relatively easy to achieve. If only one free electron is created for every 40 eV of input energy, and if the total excitation volume is 100 cm\(^3\); then just \(6 \times 10^{17}\) eV or 0.1 joule of energy is needed.

Up to this point it has been assumed that the electrons involved in recombination have only thermal velocities. Since the electrons initially have somewhat larger energies, the time required for thermalization is an important consideration. A typical electron might be released with 100 eV of energy, which is 4000 times the thermal energy of 0.025 eV. In an elastic collision with helium, the electron can lose a maximum of about \(4 \times 10^{-4}\) of its energy, because the helium atom has a mass nearly \(10^4\) times the mass of an electron. On the average an even smaller fraction of the energy will be lost per collision, so about \(10^4\) collisions are needed for thermalization.

Collisions will occur at a rate equal to the velocity of the electrons times the collisional cross section multiplied by the number density of helium atoms. The velocity of a 50-eV electron is \(4.2 \times 10^8\) cm/sec. Using this as an average velocity and assuming an atomic cross section of \(10^{-16}\) cm\(^2\), the collisions should occur at a rate of
1.35 \times 10^9 \text{sec.}^{-1}$, where $p$ is again the pressure in torr. The time required for $10^4$ collisions would then be $7.5 \times 10^{-6}/p$ seconds. Thus the pressure must be at least one atmosphere (760 torr) to thermalize the electrons in $10^{-8}$ seconds.

It is interesting to see if the thermalized electron will undergo parential recombination; that is, if it will recombine with the ion it originally came from. During the time the electron is making $10^4$ collisions, it will move away from the parent ion. Applying the random walk model,$^{18}$ one finds a total displacement of $\sqrt{10^4 \lambda}$, where $\lambda$ is the mean free path between collisions or roughly the atomic spacing. The final separation will be

$$100\lambda = 100/(N_{\text{He}})^{1/2} = 3 \times 10^{-4}/p^{1/3} \text{cm.}$$

At this distance the parent ion would have a binding energy of only $4.8 \times 10^{-4}p^{1/3}$ eV. Even at 100 atmospheres of pressure, this is less than the thermal energy, which means that the electron is not likely to experience parential recombination under normal circumstances.

One still unsolved problem arises from the fact that there are many excited states of $\text{He}_2$. The molecules are created with some unknown population distribution over these states. Since only the lowest excited state is desired, large quantities of energy could conceivably be wasted in forming more highly excited molecules. The higher states can decay to the $A^1\Sigma^+$ state by radiation and by inelastic collisions, and the emission spectrum indicates that a
large number of molecules do indeed eventually end up in this state. However, should this decay process require too much time, then it may not be possible to build up the required density of the $A'\Sigma^+$ state needed to produce lasing. It is hoped that the population of the higher states is small, and the high pressures being used should help speed up the collisional relaxation process. Further study is needed, however, to see if this is really a major obstacle to lasing.
CHAPTER III

EQUIPMENT

The laser was designed with the following characteristics in mind:

1. It must be able to provide a uniform discharge in helium gas at pressures of up to ten atmospheres.
2. It should be as long as possible.
3. Sufficient energy should be available to produce ample excited molecules for lasing to occur.
4. The current rise time must be short enough that the necessary power input level can be obtained.

Figure 3 shows a diagram of the apparatus which was constructed. The laser itself consisted of a clear lucite tube 4½ feet long, with an outside diameter of 2 inches and walls ¼ inch thick. This was mounted between two large, flat-plate capacitors. Inside the tube on one side was a solid stainless steel electrode 122 cm long and 1.2 cm wide. Facing this on the opposite wall were 154 brass pin electrodes, each protruding 1.4 cm into the tube. This left a gap of 1.2 cm between the opposing electrodes. The pin electrodes were evenly spaced along the tube at a distance of 0.79 cm. The steel electrode was connected to one of the upper capacitor plates. Each pin electrode was initially connected to a two-watt, 360-Ω resistor, which in turn was connected to the other upper copper sheet. The purpose
of these resistors was to limit the amount of current flowing through any single electrode, so that all the current could not flow across at one point but would be spread out along the tube. It was later found that when the laser was fired, arcing often occurred around some of the resistors. The current simply bypassed the resistor and leaped to the other end through the air. Pictures confirmed that most of the discharge in the tube was concentrated on those electrodes which had arcing around their resistors. The resistors were all removed and replaced with a solid strip of aluminum. The resulting discharges proved to be more uniform, and the arcing was eliminated.

The flat-plate capacitors were made of copper sheets 4 feet wide and 8 feet long, with layers of dielectric between them. The lower plates were soldered together at the center. Lead weights were placed on top of the plates to flatten them and to hold them closely together.

The dielectric initially consisted of 8 sheets of polyethylene, each 6 mils thick. The sheets were found to be rather irregular in thickness and difficult to flatten completely. They were later replaced with 8 mylar sheets with a total thickness of 40 mils. At one time the plates were immersed in distilled water in an attempt to remove the air pockets between the sheets and thus increase the capacitance. However, the water quickly became contaminated with dissolved salts from the copper plates. Also the
mylar was weakened by the water and soon broke down in several places. The final dielectric used consisted of 35 mils of mylar and 6 mils of polyethylene, with no water added. The polyethylene sheet was added because it was much wider than the mylar and therefore more effective in preventing arcing around the edges of the capacitors.

The capacitance was determined by measuring the time constant of an RC circuit containing this capacitance and a known resistance. In the final configuration, the capacitance was $0.0275 \mu f$ on each side of the tube.

The voltage on the plates was provided by a Universal Voltronics power supply with a maximum output of 60 kV. In most cases the lower plate was grounded, as was one side of the power supply. Voltage was then supplied through two 450,000-ohm resistor stacks to the upper plates. These resistors were made of strings of ten-watt, 50,000 ohm resistors, which were connected together end to end and enclosed in a plastic tube filled with transformer oil. These precautions were taken to prevent arcing to ground and to reduce corona discharges, which at high voltages appear on every poorly insulated sharp point.

The switch consisted of a thumbtack which was driven through a small hole in the upper copper sheet by means of a falling weight. The tack ruptured several layers of mylar which had a small sheet of aluminum foil between the middle two layers. The foil near the hole vaporized, and
the metal ions provided a good conductive path for the current flowing through the hole.

The gas handling system is outlined in Figure 4. One-half inch brass tubing was generally used, but the lines leading to and from the laser were made of rubber. This was necessary to prevent arcing to the gas lines from the electrodes near the ends of the tube. High purity helium was used which was certified by the supplier to be 99.997\% pure.\textsuperscript{19} The system was evacuated, flushed with nitrogen, reevacuated, and flushed with helium each time before filling.

When fully charged to 60,000 volts, the two capacitors had a total stored energy of $\frac{1}{2}CV^2$ or 100 joules. Half of this energy flows directly to ground, however, and is lost. Assuming that one can discharge the capacitors in $10^{-8}$ seconds, the lifetime of the $A^{'\Sigma^+}$ state, is there enough energy available to achieve lasing? Earlier it was shown that the threshold value of $N_u$ is $3\times10^{18}/L$ cm$^{-3}$. The total number of excited molecules needed is $N_uLA$, where $A$ is the cross-sectional area of the excitation region. The value of $A$ has been determined experimentally to be about 0.2 cm$^2$, causing one to need at least $6\times10^{17}$ total molecules in the $A^{'\Sigma^+}$ state. Each molecule is 15 eV above the ground state, giving a total of $9\times10^{18}$ eV needed to achieve threshold lasing conditions. Fifty joules is equal to $3\times10^{20}$ eV, so at least 3\% of the total available energy must end
up in the $^1\Sigma^+$ state. It was seen in liquid helium that 10% of the input power came out as ultraviolet light, but the present system is probably not nearly as efficient as was the electron bombarded liquid helium. Thus the total energy available with this equipment is at best the minimum amount necessary to achieve lasing. Since there is no excess energy, the capacitor must be discharged within $10^{-8}$ seconds to meet the power requirements.
CHAPTER IV

EXPERIMENTAL RESULTS

The laser was first tested with nitrogen gas to check for major design flaws. It was known that nitrogen gas at low pressures can be fairly easily induced to lase, producing several lines close to $3371\,\text{Å}$\textsuperscript{20} Such lasing was detected by the fluorescence it induced in a cell of rhodamine-6G dye placed along the laser axis about one meter from the end of the laser. Lasing occurred at pressures between 20 and 175 torr. As expected from previous experiments, no lasing was evident when the pressure was increased to two atmospheres.

The next gas to be tested was hydrogen. Hodgson\textsuperscript{6} has successfully operated a molecular hydrogen laser of similar design, producing several lines near $1600\,\text{Å}$. It was felt that this would be a good test of the switching apparatus, since short rise times are necessary to lase hydrogen. In order to detect lasing, the quartz plate at the end of the laser was coated with a thin film of sodium salicylate on the inside face, leaving a narrow vertical strip uncoated. The outside face was then coated only along this vertical line. Ultraviolet light striking the sodium salicylate causes it to fluoresce. However, hard ultraviolet light, such as that at $1600\,\text{Å}$, is absorbed by the quartz plate. The outside line will therefore not fluoresce when
the hydrogen lases, and one should see a bright line with a gap in the center.

Although a variety of pressures were used, no lasing was ever definitely detected. Vacuum ultraviolet light was produced, but it caused a broad, rather diffuse band of fluorescence rather than the bright, narrow line that was expected. These results were interpreted to mean that no lasing had occurred.

Although the hydrogen experiments were not encouraging, similar tests were performed with helium at ten atmospheres of pressure. Again vacuum ultraviolet light was observed, but lasing could not be confirmed.

A spectrometer was urgently needed to look at the light output from the laser. If lasing were occurring, the spectrum should show one or more intense lines rather than the broad continuum mentioned earlier. If the system were not lasing, the spectrometer could still yield valuable information about rise times of the light produced as well as the total power output. A former student had partially assembled an ultraviolet spectrometer. However, it was found to be too imprecise and of the wrong design to be of much use. A spectrometer which would have been acceptable was on loan to another university.

Attempts were next made to measure the rise time and current density of the laser discharge by means of a flux sensor. This is basically a loop of wire which is placed
with its axis parallel to the magnetic field produced by the current to be measured. When the current increases, the magnetic field likewise increases. The total magnetic flux passing through the loop will rise, thus causing a current proportional to $dB/dt$ to flow around the loop. The current flows in the horizontal plane of the laser, and consequently the magnetic field at a point above the center of the laser should point along the axis of the laser tube. The probe was suspended several inches above the laser, and the laser was fired with the axis of the loop once perpendicular to and once parallel to the magnetic field. Unfortunately the noise levels were so high that both signals looked the same. The noise, which presumably came from the discharge, lasted about two microseconds. This has been interpreted to mean that the current pulse lasts two microseconds, which is 200 times too long to achieve the desired power level.

At present no further attempts have been made to lase helium. However, there are several possible ways of improving the performance characteristics, as will now be discussed.
CHAPTER V

CONCLUSIONS

The helium ultraviolet laser project has so far been unsuccessful. There are several possible reasons why the system failed to work, and these suggest modifications which might improve its performance in the future.

The principle shortcoming appears to be the failure to dump sufficient energy into the gas in a short enough time. A faster switching device is needed, and the total potential energy stored in the capacitors should be increased. Four times more energy could be provided by doubling the voltage on the plates, and further gains could be made by increasing the capacitance. The total energy needed is directly proportional to the cross-sectional area of the excitation region. This could be reduced somewhat by decreasing the electrode spacing and by confining the gas in a thin, flat cavity rather than the wide tube that was used.

The problem of contaminants must also be considered. The first excited state of He$_2$ has enough energy to ionize any other element. Thus any contaminants in the helium will rob the system of energy and help to prevent lasing. Contamination is possible from several sources in the present system. The vacuum pump being used has a lower limit of about $10^{-4}$ torr, and a trap is needed to keep oil vapors
from backing up into the system from the pump. It is impossible to remove adsorbed gases from the interior surfaces by heating without damaging the equipment. A few very small leaks were never completely stopped, although they should contribute little when the internal pressure is more than one atmosphere. The helium gas was run through a liquid nitrogen trap before it entered the laser tube, in an attempt to further purify it. This was probably superfluous due to the larger sources of contaminants mentioned above, but it could be important when these obstacles are removed.

Another possible improvement would be to preionize some of the gas prior to firing the laser. This would provide a source of free electrons and could produce a more uniform discharge. Such preionization has been achieved in carbon dioxide lasers by using a three-electrode system. An alternate method might be to create a voltage difference between the two upper capacitor plates with a second power supply. This voltage would be adjusted to give a small continuous discharge before the laser is fired.

It was mentioned earlier that a high-current, pulsed electron accelerator might make a suitable energy source for a laser. Liquid helium is impractical as a medium because it would boil at the high power levels required. Thus once again dense helium gas will be considered. Field-emission electron beam generators known as Febetrons have been developed which are capable of producing 3-nanosecond
pulses of 420-keV electrons with a maximum current density of over 7000 Acm$^{-2}$. This is a power flux of $1.8 \times 10^{28}$ eVcm$^{-2}$sec$^{-1}$. If the electron beam penetrates L cm into the helium, the power density will be $1.8 \times 10^{28}/L$ eVcm$^{-3}$sec$^{-1}$. Probably this system is no more efficient than was liquid helium, in which 10% of the incident power was radiated as ultraviolet light. At 15 eV per photon, this would represent a radiative transition rate of $1.2 \times 10^{26}/L$ cm$^{-3}$sec$^{-1}$. To produce such a decay rate, the density of the $A_{1}^{+}$ state would be $1.2 \times 10^{18}/L$ cm$^{-3}$, since its lifetime is $10^{-5}$ sec. This is about the maximum number density of the first excited state that one can expect to obtain by this method at present. Unfortunately, the threshold value needed for lasing is $3 \times 10^{18}/L$ cm$^{-3}$. It thus appears that present Fe-betron models are inadequate to power such a laser. However this procedure holds exciting possibilities for the future, when increased power outputs may make the helium vacuum-ultraviolet laser a reality.
Table 1

Reactions of importance in the helium gas laser.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Rate Constant ((300^\circ K.))</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{He}^+ + 2\text{He} \rightarrow \text{He}_2^+ + \text{He})</td>
<td>(k_1 = 1.06 \times 10^{-31} \text{ cm}^6\text{sec}^{-1})</td>
<td>24</td>
</tr>
<tr>
<td>(\text{He}_2^+ + 2\text{He} \rightarrow \text{He}_3^+ + \text{He})</td>
<td>(k_2 &gt; 1.06 \times 10^{-31} \text{ cm}^6\text{sec}^{-1})</td>
<td>17</td>
</tr>
<tr>
<td>(\text{He}_3^+ + \text{e}^- \rightarrow \text{He}_2^* + \text{He})</td>
<td>(k_3 = 7 \times 10^{-7} \text{ cm}^3\text{sec}^{-1})</td>
<td>25</td>
</tr>
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</table>
Table 2

Secondary reactions in the helium gas laser.

<table>
<thead>
<tr>
<th>Reaction</th>
</tr>
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<tbody>
<tr>
<td>$\text{He}^* + \text{He} \rightarrow \text{He}_2^+ + e^-, \ n \geq 3$</td>
</tr>
<tr>
<td>$\text{He}^* + 2\text{He} \rightarrow \text{He}_2^* + \text{He}$</td>
</tr>
<tr>
<td>$\text{He}^* + \text{He}^* \rightarrow \text{He}^+ + \text{He} + e^-$</td>
</tr>
<tr>
<td>$\text{He}^+ + 2e^- \rightarrow \text{He}^* + e^-$</td>
</tr>
<tr>
<td>$\text{He}^+ + e^- + \text{He} \rightarrow \text{He}^* + \text{He}$</td>
</tr>
<tr>
<td>$\text{He}_2^+ + e^- \rightarrow 2\text{He}^*$</td>
</tr>
<tr>
<td>$\text{He}_2^+ + 2e^- \rightarrow \text{He}_2^* + e^-$</td>
</tr>
<tr>
<td>$\text{He}_2^+ + e^- + \text{He} \rightarrow \text{He}_2^* + \text{He}$</td>
</tr>
<tr>
<td>$\text{He}_3^+ + 2\text{He} \rightarrow \text{He}_4^+ + \text{He}$</td>
</tr>
<tr>
<td>$\text{He}_4^+ + e^- \rightarrow \text{He}_2^* + 2\text{He}$</td>
</tr>
</tbody>
</table>
Figure 1

Ultraviolet emission spectrum of electron bombarded liquid helium.
Figure 2

Potential energy curves of He$_2$.

Figure 3

Diagram of the laser and energy storage system.
Figure 4

Gas handling system.
BIBLIOGRAPHY

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