placed peak evident in the kinetic results is to be expected since the BGK model is known to predict[18] a sound attenuation which increases less rapidly than the square of the frequency.

We thus find that the hydrodynamic description gives comparable results to our kinetic model for $y \gtrsim 2$. This indicates that the hydrodynamic description is reasonable for values of κ less than $(\alpha/2v_0)=(2\lambda)^{-1}$, where λ is an effective mean free path for collision.

There is no sound theoretical basis for extrapolating to moderately dense systems. In fact, it is clear that the results obtained here are not even qualitatively correct for a strongly interacting medium where appreciable local correlations exist. However, in the region where these correlation effects do not predominate, one might expect a description based upon the linearized hydrodynamic equations to be appropriate. For example, such a description should be applicable to liquids for very long wavelength disturbances. In neutron scattering, or light scattering where the process can similarly be described in terms of density correlations, this approach will break down for those momentum transfers where explicit effects of atomic structure appear in the angular distribution of the scattering. Since structure effects do not manifest in general for $\kappa \lesssim 10^8$ cm^{-1}, Eq. (11) should provide a reasonable calculation of the scattered energy distribution at these low values of momentum transfer. This is given further plausibility by the agreement[2] obtained with experiments on incoherent neutron scattering on the basis of a simple diffusion model in this range of momentum transfer.

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Intense 584-Å Light from a Simple Continuous Helium Plasma*

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A simple source for the production of continuous cold plasmas and intense line spectra associated with a particular gas is described in its application to helium. Plasma densities and temperatures have been measured spectroscopically. When using helium or neon gas the device becomes an intense source of ionizing radiation for studies of the chemical reactions induced by the ionizing ultraviolet. The intensity of this radiation has been measured with reasonable accuracy by very simple photocells which are easily constructed in the laboratory and are only sensitive to vacuum-ultraviolet radiator; more than 10^{16} 584-Å photons per second are emitted by a 30-W source. The mechanism is via ion-electron recombination from a 1660°K plasma of $\sim 10^{13}$ ions/^{3}cm density.

I. INTRODUCTION

THE importance of ionizing radiation in inducing chemical reactions is widely recognized. For this reason we have prepared a simple intense source of ionizing ultraviolet light, monochromatic at 584 Å, to study the chemical effects of the solar ionizing ultraviolet on planetary atmospheres and surfaces in order to contribute to the scientific base of the space program.

II. METHOD

The Sherwood project—the attempt to control thermonuclear energy—has taught us a great deal about the properties of plasmas, and in particular that for helium gas. One of the principal results is that in a moderately dense helium plasma the rate of neutralization of He^+ by

$$2e^- + He^+ = He + e^- \tag{1}$$

is very rapid.[1] In addition good methods are available for the measurement of plasma temperatures and densities.[1] With the temperatures and densities known the rate of the three-body ion-electron recombination can be calculated.[2,3] and compared with the observed intensity of the 584-Å $2\,^1P - 1\,^1S$ line.

Our source is a very simple and low-power device for producing plasmas of ~ 1660°K and number densities of 10^{13} cm^{-3} over a volume of several cubic centimeters. We find an intensity of $\sim 4\times 10^{15}$ 584-Å photons per second cubic centimeter.

* This research was supported by the Directorate of Chemical Sciences, U. S. Air Force Office of Scientific Research, Grant No. AF-AFOSR 245-64.

[1] E. Hinnov and J. G. Hirschberg, Phys. Rev. **125**, 795 (1962).
[2] F. Robben, W. B. Kunkel, and L. Talbot, Phys. Rev. **132**, 2363 (1963).
[3] D. R. Bates, A. E. Kingston, and R. W. P. McWhirter, Proc. Roy Soc. (London) **A267**, 297 (1962); **A270**, 155 (1962).

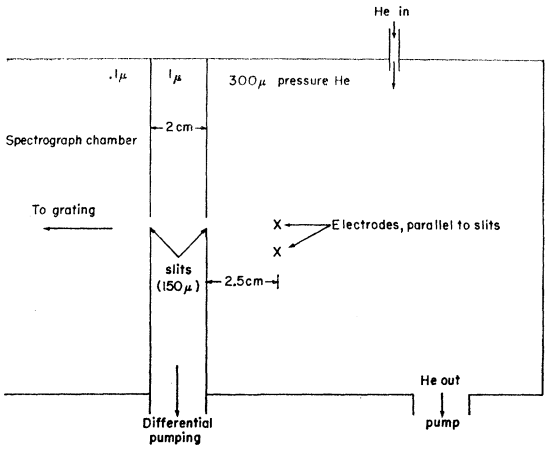

FIG. 1. A sketch of the source itself and the way in which it is mounted with respect to the spectrograph. The electrodes are represented by crosses with one electrode in spectrograph light acceptance cone.

III. THE PLASMA SOURCE

The source itself consists of a thoriated tungsten wire as hot cathode and a tantalum wire as anode encaged in a large metal cannister. Typical operating conditions are 300-μ helium pressure and 30 V applied to the anode with 1 A flowing. The exact source dimensions and geometry are not critical but the work reported here applies to the following arrangement: 3-cm-long cathode of 0.010-in. thoriated tungsten parallel to and 1 cm from a 3 cm 0.020-in. tantalum wire serving as anode (Fig. 1). The device has several current modes depending on cathode temperature, anode voltage, and helium pressure. The low-current mode is equivalent to ordinary operation of a vacuum diode tube; the intermediate-current mode of hundreds of milliamperes to a few tens of amperes is the condition in which the device operates as described in this paper; the high-current mode is a typical low-pressure arc. If the pressure drops to less than 50 μ or the cathode temperature is too low to cause significant thermionic emission, or the anode voltage falls to less than 22 V, the device drops into the low-current mode. The transition is gradual in the case of varying cathode temperature but very abrupt in pressure or anode voltage. A drop of less than 0.1 V will cause the current to change from many amperes to a few milliamperes. With very pure helium and well-outgassed electrodes the process is reversible at the same voltage; otherwise there is a hysterisis effect and a higher starting voltage is necessary, although again the current goes from milliamperes to amperes in $\sim$0.1 V. In the intermediate-current mode, anode current is determined primarily by cathode temperature. Anode voltage has little effect once it has been raised past the striking level. Separation between cathode and anode has been increased to 7 cm with no appreciable increase in anode voltage required. The limiting factor on the current is the amount of heat the anode can dissipate before it melts, or the heat the lead in conductors can dissipate. These must be $\sim\frac{1}{4}$ in. in diameter if they are not water cooled. In the intermediate-current mode the source resistance is positive and therefore no resistance is required in series with it to give stable operation. With a very stable low-output-impedance power supply there was no evidence of oscillations up to frequencies of 100 Mc/sec. The high-current mode occurs when anode potentials are increased to several hundred volts. This is a typical low-pressure arc and a resistor must be placed in series with the source to obtain stable operation.

The intensity of 584-Å light is greatest from the cathode region and reaches a maximum a millimeter or so from the cathode in the direction away from the anode (Fig. 2). Light intensity is roughly proportional to current and inversely proportional to anode voltage (Figs. 3 and 4). A maximum 584-Å intensity is obtained at around 300-μ helium pressure (Fig. 5).

The spectrograph is a McPherson model 225. With the differential pumping slit, which was attached to the spectrograph, 2.5 cm from the source the spectrum consists only of the 584-Å $2\,^1P-1\,^1S$ resonance line in the extreme ultraviolet. Even the 537-Å $3\,^1P-1\,^1S$ line is usually too weak to observe. At 0.6 A the intensity of the 584-Å line is 4×10^{15} photons/sec/cm^3 near the cathode region. This intensity was determined by using a photocell with a gold photocathode. The quantum efficiency of such a photocathode is known.[4,5] The

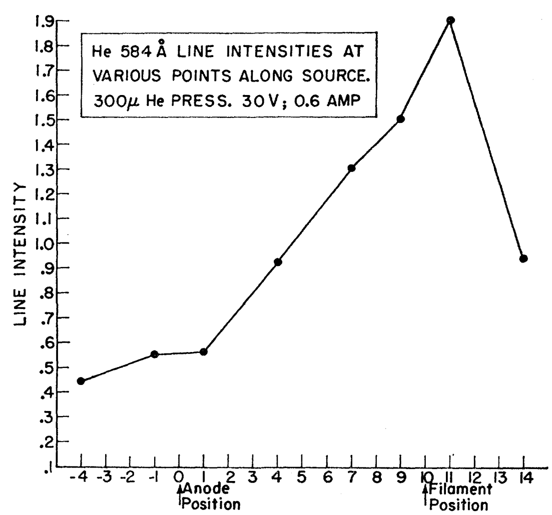

FIG. 2. Relative light intensity at 584 Å with respect to the source region being sampled by the spectrograph slit. The position of zero distance corresponds to the anode, while the 10-mm position corresponds to looking directly at the filament. Distances are $\pm$1 mm. The slit is sampling light from a region 0.2 mm wide.

[4] H. E. Hinterreger and K. Watanabe, J. Opt. Soc. Am. 43, 604 (1952).

[5] W. C. Walker, O. P. Rustgi, and G. L. Weissler, J. Appl. Phys. 26, 1366 (1955); W. C. Walker, L. R. Canfield, and G. L. Weissler, J. Opt. Soc. Am. 49, 471 (1959).

grating efficiency for the spectrograph was obtained by measuring the intensity of the line before and after reflection from the grating with this photocell. For this measurement a 2000-Å-thick aluminum foil was used in front of the photocell to filter out hydrogen Lyman alpha (Ly_α) radiation (1216 Å) and stop ions and electrons when measuring the intensity of the direct beam. The transmissions of the filter to 584- and 1216-Å radiation were measured. Thin aluminum foils transmit quite well in the extreme ultraviolet up to wavelengths of about 1000-Å at which point their optical density increases until a 2000-Å-thick foil is essentially opaque in the near ultraviolet and visible.[6,7] At the same time the quantum efficiency of the gold photocathode decreases rapidly above 1000-Å. The combination of the two effects can be used to make a very sensitive photocell in the vacuum ultraviolet, which is essentially insensitive to light whose wavelength is greater than 2000-Å. With this information and a calculation of the light passed by the spectrograph entrance slit the absolute intensity of the 584-Å line can be determined. The quantum efficiency of the gold photocell is probably not known to better than a 50% accuracy. The value chosen was on the low side so that the intensity could be 50% greater than reported.

The intensity of the Ly_α light probably depends mainly on the anode purity (which we did not cool) as well as on the purity of the helium gas and the cleanliness of the vacuum system. It is generated principally when impurity molecules containing hydrogen give electrons to the He^+ ions because of the higher ionization potential of helium. When using mass-spectrographic grade helium or helium evaporated from the liquid, the Ly_α intensity was about the same as the

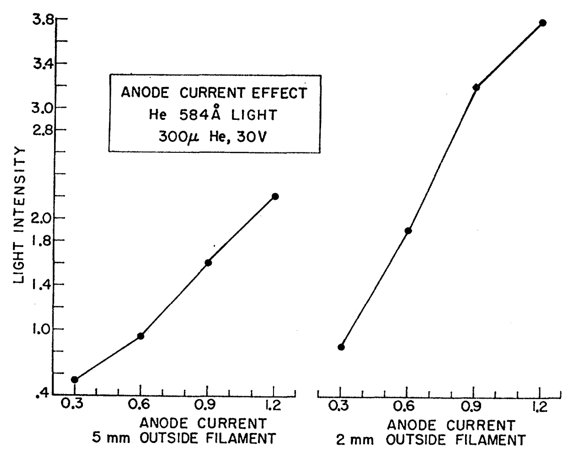

FIG. 3. Variation of relative 584-Å light intensity with respect to anode current. The 5-mm position corresponds to the 15-mm position in Fig. 2. The 2-mm position corresponds to 12 mm in Fig. 2.

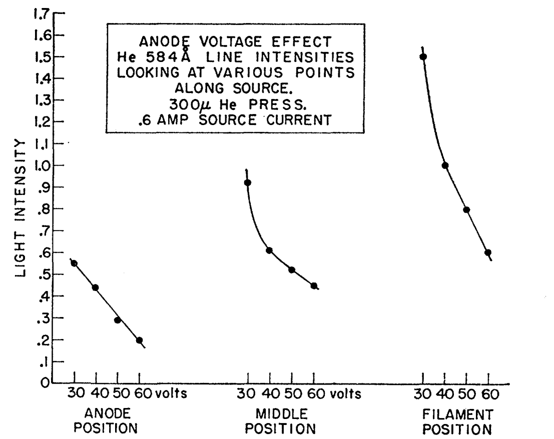

FIG. 4. Variation of 584-Å light intensity with respect to anode voltage. Three curves are shown with the slit looking at the anode, the region halfway between the anode and cathode, and the cathode, respectively.

584-Å intensity in terms of numbers of photons per second. It is for this reason that we believe anode cooling would reduce the Ly_α dramatically.

There is a weak doublet of unknown origin at 1300 Å and a few other very weak lines below 2000 Å. Above 2000 Å the other helium emission lines and a few impurity lines appear. The spectrum resembles that produced by a radio-frequency discharge source. No evidence of light from the He_2^+ molecule ion is seen.[8] The source is clean in several regions where He_2^+ bands would appear, especially in the 600–900-Å region and also for the 5133-Å band, and they are not observed.

Various different electrode geometries have been investigated as well as varying numbers of electrodes. The intensity of 584-Å radiation remains roughly the same for a given current. Since the light comes, we believe, from bound states formed by ion-electron recombination, the ion densities are not appreciably altered by the number or arrangement of electrodes; nor does the ion density vary rapidly in going from cathode to anode as Fig. 2 shows; however, accurate interpretation of this variation must be done in terms of both electron temperature and ion densities. For the studies described here the simple two-wire arrangement previously described is best. This is because the entrance slit of the spectrograph may be arranged so that it is parallel to the plane of the two wires and the light then can be sampled from a thin plane-shaped region which is perpendicular to the plane of the two wires.

IV. PLASMA DENSITY AND TEMPERATURE

Work done on the decaying plasma of the B-1 stellarator at Princeton by Hinnov and Hirschberg[1] has

[6] R. P. Madden, L. R. Canfield, and G. Hass, J. Opt. Soc. Am. 53, 620 (1963).
[7] G. Hass and J. E. Waylonis, J. Opt. Soc. Am. **50**, 1133 (1960).
[8] R. W. Motley and A. F. Kuckes, *Proceedings of the Fifth International Conference on Ionization Phenomena in Gases, Munich*, 1962 (North-Holland Publishing Company, Amsterdam, 1962), Vol. 1, p. 651.

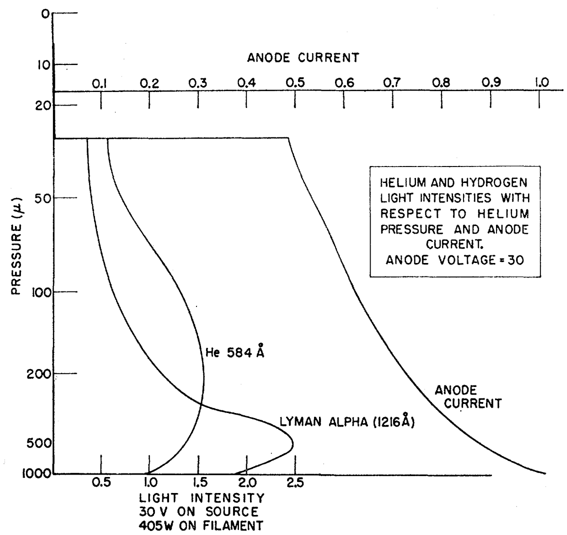

FIG. 5. The two curves to the left show the intensity of He 584-Å light and Lyman alpha (1216-Å) light with respect to helium pressure. The curve to the right gives the source current with respect to pressure for the given anode voltage and filament temperature. Note the sharp shoulder for all three curves at ~30 μ where the source switches into the intermediate-current mode.

established a convenient and reliable spectroscopic method for determining electron density and temperature. This procedure was used by Robben, Kunkel, and Talbot[2] to determine the ion densities and temperatures in a plasma-jet wind tunnel. This procedure depends on electron-collision-induced transitions being dominant over purely radiative transitions. When this condition is met a kind of thermal equilibrium between electrons and the bound states near the ionization limit is established, providing the difference in energy between any two neighboring bound states be small compared to kT. Then the densities of these bound states, their energies with respect to the ionization potential, and the electron temperature will be related by the Boltzmann equation:

$$\Delta E_{n,m}/kT=\ln(N_n/N_m). \qquad (2)$$

$\Delta E_{n,m}$ is the difference in energy between states n and m and $\ln(N_n/N_m)$ is the logarithm of the ratio of the densities of the two states.

The densities of these states were determined by measuring the absolute intensities of their spectral lines and dividing these intensities by the corresponding transition probabilities. The transition probabilities were calculated from the same oscillator strengths as used by Robben *et al.* These are based on theoretical calculations by Bates and Damgaard,[9] and Trefftz *et al.*[10] by both the the Coulomb expansion and variational techniques, which agree quite closely.

The absolute intensities of lines up to principal quantum number, $n=9$, were measured. Unfortunately, the spectrograph used was primarily a vacuum ultraviolet instrument and absolute values of line intensities of lines originating from states higher than $n=9$ did not prove to be reliable; nor could the point where the lines merged into the continuum be observed, which would have provided a check on calculated electron densities via the Inglis-Teller equation.[11] Fortunately, the electron temperature was high enough so that the Boltzmann relation held down to states with $n=5$. The plot of the logarithm of the state density divided by state multiplicity with respect to state energy is shown in Fig. 6. The slope corresponds to a plasma temperature of 1660°K near the cathode. The extrapolation of the line to $E=0$ gives the logarithm of $(N_n/g_n)e^{-E_n/kT}$. This is related to electron density by the Saha equation:

$$N_eN_i/g_eg_i=N_n/g_n(2\pi mkT/h^2)^{3/2}e^{-E_n/kT}, \qquad (3)$$

where N_e, N_i, and N_n are the number densities of the electrons, ions, and bound states, respectively, and the g's are their multiplicities; $-E_n$ is the energy of the bound state; $g_eg_i(2\pi mk/h^2)^{3/2}=1.2\times10^{22}$ if T is to be in electron volts.

Since the space-charge limited current of the device is only a few milliamperes in the absence of positive charges, the charge density of the electrons must be essentially balanced by the charge density of the He^+ ions for currents of amperes to flow. Therefore, setting $N_e=N_i$ is justified and

$$N_e^2=N_i^2=1.2\times10^{22}T^{3/2}(N_n/g_n)e^{-E_n/kT}. \qquad (4)$$

The average ion density near the cathode is then determined to be 8.4×10^{12} ions/cm³ at 30-V anode voltage and 0.6-A anode current. The temperature near the cathode is 1660°K, and the average intensity of 584-Å light is 4×10^{15} photon/sec/cm³. The ion density

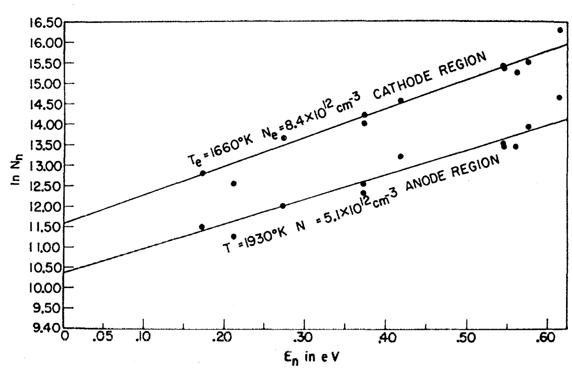

FIG. 6. The two straight lines are best fits for the plot of ln (N_n/g_n) with respect to E_n. The upper line is drawn through data points obtained when the spectrograph slit was directed toward the cathode. The lower curve corresponds to the anode.

[9] D. R. Bates and A. Damgaard, Phil. Trans. Roy. Soc. (London) A242, 101 (1949).

[10] E. Trefftz, A. Schluter, K. Dettmar, and K. Jorgens, Z. Astrophys. 44, 1 (1957).

[11] D. R. Inglis and E. Teller, Astrophys. J. 90, 439 (1939).

near the anode is 5×10^{12} cm^{-3} at a temperature of $\sim$1900°K. The intensity of 584-Å light from the anode region is $\sim10^{15}$ photons/sec/cm^3.

In order to properly interpret the observed intensity of 584-Å radiation, it is necessary to determine the extent to which it is resonance imprisoned. Trapped radiation will be scattered out of the acceptance cone of the spectrograph and will not be seen by it. At 300-μ helium pressure and room temperature the mean free path of 584-Å radiation at the resonance peak is 0.0016 cm. Certainly, then, much of it is trapped.

At these ion densities, pressures, and temperatures, the principal broadening mechanism is the Doppler effect due to temperature. Since the helium $2\,^1P$ atoms which have been formed as a result of ionic recombination will be considerably hotter than the neutral helium atoms, their emitted light will be Doppler shifted further and will be expected to travel further through the surrounding helium gas, which is at room temperature. These excited helium atoms will usually have undergone only electronic collisions between the time they are formed from the ions and the time they emit 584-Å radiation. They will therefore retain the temperatures associated with the ions.

The 584-Å photons must travel through 2.5 cm of helium at 300 μ to reach the differential pumping slit, at which point they will not be significantly further scattered in the spectrograph, and their intensity is measured. If one introduces into the light path an additional amount of helium at 300 μ as an absorber, the 584-Å radiation will be further attenuated. The extent to which it is attenuated will depend on the temperatures of the emitting and absorbing atoms, and on the distance which the light has already traveled through the absorbing helium. The exact relation for the intensity reaching a given point in the absorber, with the assumption that any scattered photons are lost, is

$$I_\lambda=\int_0^{-\infty}\exp\left\{-\left[\frac{Mv^2}{kT_\sigma}+P_0\lambda\exp\left(-\frac{Mv^2}{kT_\alpha}\right)\right]\right\}dv\,.$$

I_λ is the intensity λ cm from the emitter, v the velocity of emitting atom toward or away from observer, T_σ the temperature of the emitting atom, T_α the temperature of absorbing atoms, M the mass of a helium atom, and P_0 equals 600 cm^{-1}, the absorption coefficient of 300°K helium at 300-μ pressure. Thus, it is improper to speak of a mean free path when the absorber is helium, since the absorption is not an exponential function of λ.

Observations on the 584-Å radiation from the helium plasma give $I_{12.5}/I_{2.5}=0.70$. This is what one would expect for $T_\sigma\approx1700$°K. For $T_\sigma\approx300$°K $I_{12.5}/I_{2.5}<0.19$. Therefore we conclude that the emitting atoms are at $\approx$1700°K.

At $T_\sigma=1700$°K $I_{2.5}/I_0=0.102$. The average ion density near the cathode is $\sim10^{13}$/cm^3; however, it is higher, $\sim2.5\times10^{13}$/cm^3, very near the cathode. At $\sim2.5\times10^{-13}$ ions/cm^3 the recombination coefficient is $\sim2.5\times10^{-10}$ cm^3/sec, taking the value of Bates *et al.*,[2,3,12] which are one-half as large as those of Hinnov and Hirschberg.[1] If one assumed that all of the recombined atoms eventually emit 584-Å radiation, due to electronic mixing between the singlet and triplet states, one would then expect to observe

$$\sim15\times10^{16}\times I_{2.5}/I_0=1.5\times10^{16}\text{ photons/sec/cm}^3.$$

This agrees very well with the observed light intensity and the ion densities calculated above for these regions. On the basis of all of these considerations we conclude that ionic recombination by reaction (1) is the mechanism of light emission.

However, a further additional point to consider is the extent to which light produced by $2\,^1P$ helium atoms excited directly from the ground state would be observed. This cross section for electrons[13,14] of energies less than 30 V is less than 1×10^{-18} cm^2. Therefore we expect, at 0.6 amperes and 300-μ pressure, that less than 3.6×10^{16} $2\,^1P$ excitations would occur in one second. Since $I_{2.5}/I_0$ for $T_\sigma\approx300$°K is less than 0.001, one would observe less than 3.6×10^{13} 584-Å photons per second from this mechanism.

Another point is that the peak in the light intensity is near the cathode. One would not ordinarily think that electrons would achieve the necessary minimum of 21.5 eV so near the cathode when total anode voltage can be as low as 22 V. However, ions will be concentrated near the cathode and will recombine more rapidly there.

V. SOURCE MECHANISM

Origin of the ions: Since the space-charge-limited current of the device described in the absence of positive charges is of the order of milliamperes, positive ions must be present to neutralize the space charge in order that currents as large as amperes could flow. Because the source can be operated at potentials significantly below the 24.5-V ionization potential of helium, it is unlikely that ionization directly from the ground state is involved. A two-step process involving excitation to the $2\,^3S$ metastable state with a maximum cross section of 4×10^{-18} cm^2 at 20.5 eV,[15] and subsequent ionization by a second electron with a cross section estimated to be $>10^{-16}$ cm^2 (by comparing He 2^3S to lithium[16]) is possible. Another possibility is the formation of the triplet state followed by triplet-triplet annihilation to produce an ion, electron, and atom in the ground state. The triplet-triplet annihilation cross sections are very large ($\sim10^{-14}$ cm^2).[17]

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[12] G. L. Natason, Zh. Tekhn. Fiz. **29**, 1373 (1959) [English transl.: Soviet Phys—Tech. Phys., 4, 1263 (1960)].
[13] D. R. Bates, *Atomic and Molecular Processes* (Academic Press, Inc., New York, 1962), p. 262.
[14] O. Thieme, Z. Physik. **78**, 412 (1932).
[15] G. J. Schultz and R. E. Fox, Phys. Rev. **106**, 1179 (1957).
[16] H. Funk, Ann. Physik **396**, 149 (1930).
[17] A. V. Phelps and J. P. Molnar, Phys. Rev. **89**, 1202 (1953).

The source of Ly_α radiation is charge or energy transfer from ions or metastable atoms to impurities containing hydrogen. Thus, the maximum observed Ly_α intensity of $\sim 10^{18}$ photons per second is of interest in indicating the total possible rate of production of ions and metastable atoms. However, this Ly_α intensity was observed by injecting H_2 gas into the system. This caused the He 584-Å line to almost disappear, so that the source mechanism may have been modified somewhat.

A closer examination of the characteristics of the device reveals several other interesting features. If there were no current flowing, 60% of the total potential applied would be developed within 3 mm of the cathode, since it is a 0.010-in.-diam wire and the anode is 0.020 in. in diameter. However, the presence and distribution of ions and electrons changes this picture. Both species are present near the cathode and the incoming ions can neutralize the charge of the outgoing electrons. The same is true for most of the region in between the two electrodes. However, ions must be produced a finite distance from the anode and they will be accelerated away from it. There will then be no space-charge neutralization in a small sheath surrounding the anode; while the large currents will cause enormous fields to be developed in this region. The anode will then require the use of most of the applied potential to pull the electrons into it. The situation is almost the reverse of the potential distribution in an ordinary gas discharge tube. Using the calculated ion densites and the measured drift velocities of electrons in helium[18] we find, in fact, that field strengths near the cathode ($\sim$1.5 mm) are $<$3 V/cm.

This means that ions and electrons will have relatively small forces on them in the cathode region, requiring high charge densities to maintain the observed currents. At the same time there will be a low temperature, since the temperature is built up by random velocity orientations induced by collisions of the particles accelerated by the field. This will be especially true in the region near the cathode but farthest from the anode, i.e., looking away from the anode. The high ion density caused by approach to the small cathode and the low temperature will be ideal for the recombination of ions and electrons. The recombination coefficient increases rapidly with decreasing temperature and increasing ion density.[1] These facts also explain the observed decrease in light intensity with increase in anode potential. The effect of the increase in potential is to raise plasma temperatures and decrease ion densities, since less will be needed to maintain a given current. Both of these effects will reduce the rate of recombination.

[18] J. A. Hornbeck, Phys. Rev. **83**, 374 (1951).

VI. OTHER APPLICATIONS

By a reversal of the technique used for measuring plasma temperature and density the system becomes a convenient and precise laboratory for the measurement of oscillator strengths and dipole moments in excited states of more complicated atoms such as the heavier noble gases.

Operation at higher pressures will produce a continuous and intense source of molecule ions such as He_2^+ together with information about their production cross sections and recombination coefficients.

At this point one ought to emphasize the simplicity of the device. This plasma source can be constructed and operated on the most modest budget. Temperature, density, and physical dimensions of the plasma can be varied over wide ranges. Density is varied by adjusting the anode current. Temperature is determined by the anode voltage and the gas pressure. The device may be made quite large so that a fairly extensive plasma is created. And the operation is continuous, so that measurements on it may be made at a convenient pace and without the necessity of rapid-response instrumentation. All this combined with the fact that plasmas of appreciable densities are not really readily available to most researches at any cost make this plasma source most attractive for a variety of problems ranging from studies of recombination rates to Stark broadening.

ACKNOWLEDGMENTS

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