THE ENERGY OF THERMAL ELECTRONS IN ELECTRON BEAM CREATED HELIUM DISCHARGES ☆

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We have measured the electron energy of the thermal group of electrons in both longitudinal and transverse electron beam created helium glow discharges. The measurement technique employs the ratio of intensities of spectral lines in the $2s\,^3S$–$np\,^3P$ He I series. Values of kT_e between 0.07 and 0.11 eV were obtained. These energies are typical of the beam-generated electric field free plasmas. The comptetitive loss of helium ions by recombination and by charge transfer in a He–Hg electron beam created plasma is calculated. The results are applied to the Hg^+ laser pumping scheme using a electron beam created He–Hg plasma.

Recently, we demonstrated that electron beam created glow discharges may be employed as a new active medium for CW ion lasers [1–4]. We have developed glow discharge electron guns for both longitudinal [5,6] and transverse [7] plasma excitation. These electron guns produce electron-beam currents up to 1 A at energies between 1 and 10 keV.

Fig. 1 shows the calculated electron energy distribution in the electron beam generated helium plasma obtained by solving the Boltzmann equation in the electric field free negative glow region [8]. Although the ionization is due to collisions of gas atoms with high- and intermediate-energy electrons, the most numerous group of electrons in the negative glow has near thermal energy (see fig. 1). This is because the

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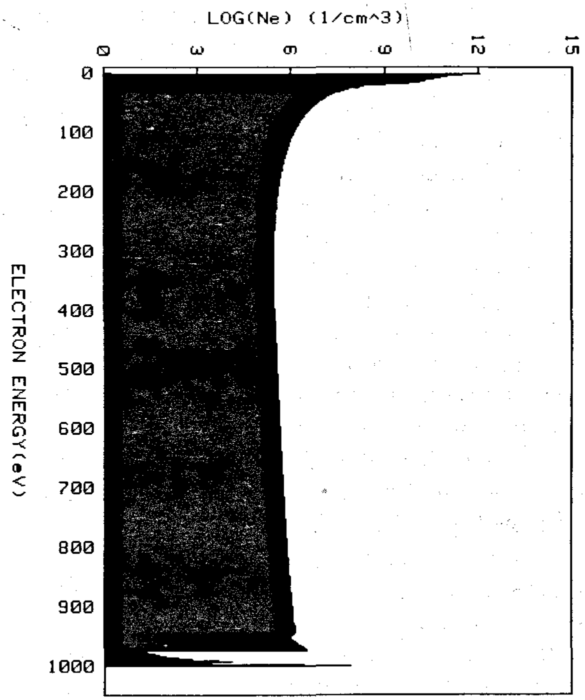

Fig. 1. Calculated electron energy distribution for helium plasma excited by a 1 keV electron beam. He density $6 \times 10^{16}\ cm^{-3}$.

differential cross section for the production of secondary electrons in ionizing electron–atom collisions peaks at zero energy [9]. Moreover, each beam electron can create numerous secondary electrons. These secondary electrons gain energy via superelastic collisions with excited atoms, elastic collisions with beam electrons or as a result of three-body electron–ion recombination and are thermalized by elastic collisions in the field-free negative glow region.

We have measured the electron temperature of the thermal energy group of electrons in the negative glow of both longitudinal and transverse glow discharges using the ratio of spectral intensities of the 2s ^{3}S–np ^{3}P He I series.

Knowledge of the temperature of this thermal electron group is necessary to determine if the plasma is diffusion or recombination dominated [10], since collisionally assisted (three-body) electron–ion recombination is proportional to $T_e^{-4.3}$ [11]. In a charge transfer ion laser electron recombination represents a loss of buffer gas ions, thereby limiting output power and efficiency. Also, if the plasma is to be used as laser active medium these low-energy electrons will play an important role in the electron de-excitation of the laser levels [12].

The longitudinally excited electron-beam plasma was created using a glow discharge electron gun similar to the one described in ref. [6] and having a LaB_6 cathode 3.2 cm in diameter. The electron gun was introduced into a stainless-steel vacuum chamber having suprasil quartz windows for optical measurements. The metal chamber was grounded and served as the anode of the glow discharge. The line intensity measurements took place approximately 10 cm from the cathode emitting surface, far from the cathode dark space and well into the field-free negative glow region.

The transverse electron-beam discharge was established in the same vacuum chamber by replacing the electron gun described above by two transverse electron guns similar to the ones described in ref. [7]. They were positioned parallel facing each other as indicated in fig. 1 of ref. [7] with the distance between the cathode emitting surfaces of 3 cm. The cathodes were slotless, 5 cm long by 1.2 cm wide with a radius of curvature of 1.5 cm. Again, line intensity measurements were made in the negative glow, in the central portion of the discharge. We also have measured the electron temperature in a longitudinal electron-beam He plasma confined by a magnetic field. In this case the e$^-$ beam created plasma arrangement was similar to the one we used to obtain laser action in various He–metal vapor mixtures, described in detail in refs. [1,2]. The only difference being the use of two electron guns, one at each end of the electromagnet, to increase plasma uniformity.

The spontaneous emission from the electron beam excited plasma was collected through a suprasil window and focused into the slit of a 1 m SPEX spectrometer by a quartz lens. We used an RCA C31034 Peltier cooled photomultiplier. The spectral response of the entire optical detection system was measured using a tungsten ribbon lamp calibrated at N.B.S. so that the measurements of relative intensities were properly corrected. The ratio of intensities I, of the lines of the 2s ^{3}S–np ^{3}P He I series, assuming the levels are in local thermodynamic equilibrium (LTE) is related to kT_e by:

$$kT_e = -\Delta E(n', n) \times \{\ln[(\lambda')^3 (n')^3 I(n' \to 2)/\lambda^3 n^3 I(n \to 2)]\}^{-1} , \quad (1)$$

where $\Delta E(n', n)$ is the difference of energy between levels n and n', λ' and λ are the wavelengths of the radiation originating from the n' and n levels respectively. This equation for kT_e is particularly sensitive to measurement errors of relative intensities for high values of n and n'. A remedy is to extend the range of measurements over a large number of Rydberg levels. A plot of $\ln(1/\lambda^3 n^3 I)$ versus $E(n)$ where $E(n)$ is the energy level n, yields the average electron temperature from the slope of a line connecting the data points.

Griem [13] has formulated an approximate electron density criterion for a hydrogenic level n to be within 10% LTE with the neighboring level $n + 1$

$$n_e \geqslant (7.4 \times 10^{18}/n^{17/2})(kT_e/13.6)^{1/2} \times \exp(\Delta E_{(n,n+1)}/kT_e) . \quad (2)$$

Notice that kT_e is in eV. For an electron temperature of 0.1 eV and $n = 8$, eq. (2) requires an electron density in excess of 2.1×10^{10} cm^{-3}. Under the discharge condition of these experiments the electron density in the negative glow of the electron-beam discharge is judged to be always $>10^{11}$ cm^{-3}. Consequently all the levels with $n \geqslant 8$ should be in LTE and the plots of the 2s ^{3}S–np ^{3}P helium series are expected to give the temperature of the thermal electrons in the electron beam discharge.

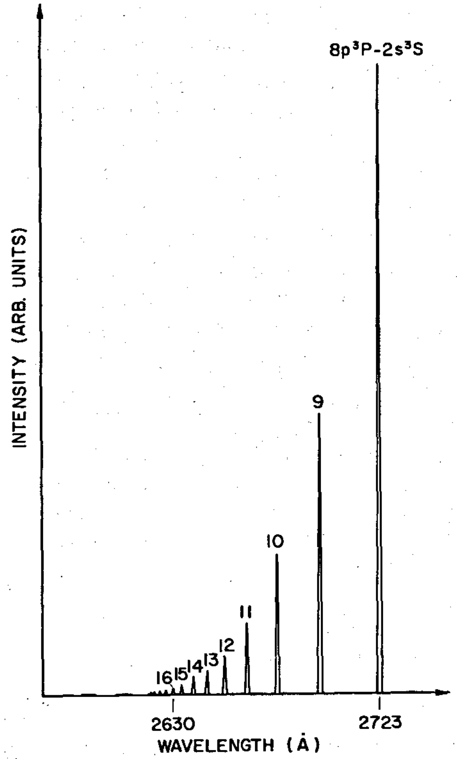

Fig. 2. 2s ^{3}S–np ^{3}P He I series spectrum in a He plasma longitudinally excited by a 0.1 A/cm^2, 2 keV electron beam. Helium pressure 2 Torr.

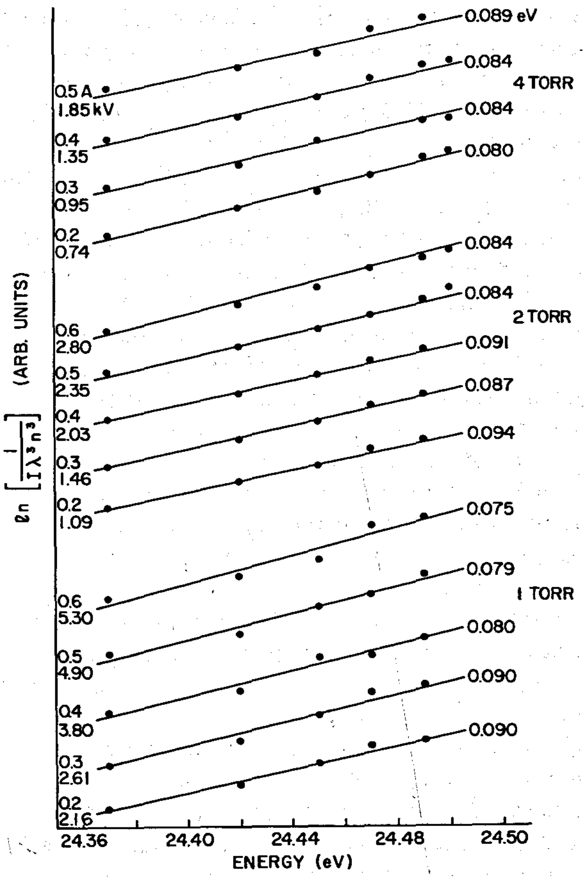

Fig. 3. Semilogarithmic plots of the line intensities of the 2s ^{3}S–np ^{3}P He I series in a helium plasma excited by a longitudinal electron beam. Helium pressure, electron beam current and voltage are indicated for each plot on the left. The corresponding values of kT_e are indicated at the right of each plot.

A scan of the 2s ^{3}S–np ^{3}P helium series for $n \geqslant 8$ taken at 2 Torr of helium at an electron gun voltage of 2 kV and a current of 75 mA is shown in fig. 2. Graphs of $\ln(1/\lambda^3 n^3 I)$ versus $E(n)$ for the longitudinal glow discharges are shown in fig. 3 for different discharge conditions. The data for each condition were fit to a straight line using a weighted least-squares-fit routine. The relative errors in the determination of the slopes, taken as one standard deviation, were between 15 and 30%. The standard deviations of kT_e, corresponding to a set of four spectral recordings repeated at the same discharge conditions, were between 4 and 13%. At helium pressures between 1 and 4 Torr, currents between 0.1 and 0.6 A and electron energies between 0.75 and 5.3 keV, the longitudinal discharges had values of kT_e for the thermal electrons between 0.075 and 0.105 eV. Measurements done in the transverse discharge at pressures between 1 and 3 Torr, currents between 0.05 and 0.5 A and voltages between 0.6 and 1 keV give similar electron energy values for the thermal electrons between 0.066 and 0.96 eV. Variations of kT_e as a function of current and pressure in the range mentioned above are within the error range of the measurements. Measurements done in the electron beam plasma confined by a 2.7 kG axial magnetic field at pressures between 2 and 4 Torr, electron beam energies between 1.2 and 3 kV and at a discharge current of 0.25 A gave electron energies between 0.090 and 0.101 eV. For a few discharge conditions we also independently measured the electron temperature using the 2s^1 S–np ^{1}P He I series obtaining, as expected, good agreement with the results obtained using the 2s ^{3}S–np ^{3}P series.

The electron temperatures measured are in good agreement with previous measurements ($kT_e = 0.094$ eV) by Persson in the negative glow of a brush cathode discharge operating at 1 Torr of helium at a current of 150 mA [10]. Moreover, the electron temperatures measured in the negative glow of hollow cathode discharges have similar values. Warner [14] measured values of kT_e for the thermal electrons between 0.068 and 0.1 eV in a planar hollow cathode discharge operating at pressures of 8 and 4 Torr. McNeil [15] measured electron energies between 0.07 and 0.15 eV in a slotted hollow cathode discharge operating at pressures between 7 and 16 Torr of He. All the above glow discharges are electron-beam generated and essentially field free in the negative glow. The most numerous electrons in the negative glow of this discharge are secondary electrons, created predominantly at zero energy, from ionization processes. These electrons gain energy from superelastic collisions, elastic collisions with energetic electrons and three-body recombination processes. However, the fact that there is no electric field in the negative glow and the large number of elastic collisions keeps the electron temperature thermal.

Knowing the value of the electron temperature of the numerous thermal electrons the importance of electron recombination as a loss mechanism of ions in this electron beam created plasma can be calculated. The quantitative values of the various creation and loss mechanisms of ground-state buffer gas ions is important in charge-transfer electron-beam pump lasers. In particular we will consider the losses of He^+ in a He–Hg electron-beam pumped laser plasma. We assume that the loss mechanisms for helium ions are: thermal charge-transfer collisions with Hg atoms; collisionally assisted three-body recombination; radiative electron recombination; and diffusion to the walls. In an electron-beam laser plasma of the kind used in ref. [1], with mercury vapor density, Hg, between 1×10^{15} and 1×10^{16} and $kT_e = 0.1$ eV the last two processes are negligibly small compared with the first two.

Consequently the fraction of ions loss by three-body electron recombination, F_R, is:

$$F_R = \frac{A(T_e/300)^{-4.3} N_e^2}{K[\mathrm{Hg}] + A(T_e/300)^{-4.3} N_e^2},$$

where $A = 7.1 \times 10^{-20}$ cm^6/s [11] and $K = v^* \sigma$, is the charge-transfer rate constant, where $\sigma = 1.4 \times 10^{14}$ cm^2 is the total velocity-averaged cross section [16] for

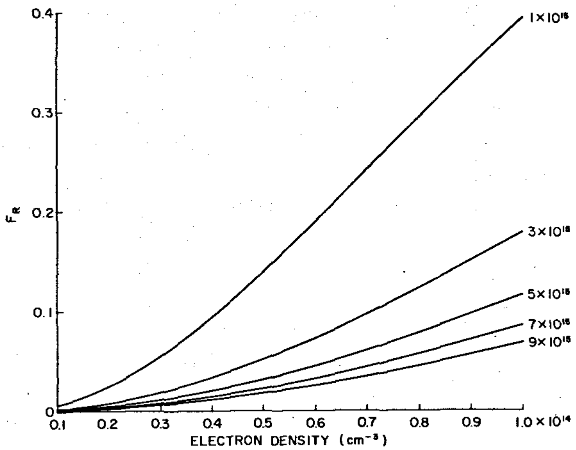

Fig. 4. Fraction of helium ions loss by recombination in a He–Hg plasma with $kT_e = 0.1$ eV as a function of electron density for the different Hg concentrations indicated at the right of the plot.

the charge-transfer reaction:

$$He^+(^2S_{1/2}) + Hg(^1S_0) \rightarrow He(^1S_0) + Hg^+(7p\,^2P) + \Delta E.$$

Fig. 4 shows the fraction of ions lost by collisionally assisted (three-body) electron recombination as a function of the electron density, for a plasma with $kT_e = 0.1$ eV, for various Hg concentrations. Electron densities up to 1×10^{14} cm^{-3} are considered. Larger electron densities are not of great interest in the case of a cw Hg^+ laser operating at 6149.9 Å because the upper laser level would be strongly depopulated by superelastic electron collisions. The atomic temperature was chosen to be 1000 K, since there cannot be a large temperature difference between the electron gas and the parent gas in a beam-generated plasma [10]. For Hg concentrations $\geqslant 3 \times 10^{15}$ cm^{-3} electron recombination losses of He^+ are small (<20%) for electron densities below 10^{14} cm^{-3}. If the Hg concentration is decreased recombination will be an increasingly important loss mechanism of He^+ ions and the efficiency of the laser would decrease. However, it is important to notice that the Hg vapor concentration cannot be arbitrarily increased since Hg has a total ionization cross section peak value more than 10 times larger than He and the amount of electron-beam power loss in electron-impact ionization and excitation of Hg^+ would also limit the efficiency of a charge-transfer pumped He–Hg^+ laser. The conclusions of fig. 4 can also be applied to other He–metal vapor ion lasers. Since the thermal charge-transfer cross sections between He^+ and Hg is the largest measured, the relative importance of electron recombination as a loss mechanism of He^+ is larger in other systems, and can be the main loss channel for He^+ if the metal vapor concentration is low ($<5 \times 10^{14}$ cm^{-3}) when the device is operated at high electron densities.

In summary, we have measured the electron temperature of the numerous low-energy electrons in both longitudinal and transverse electron beam created helium glow discharges using line intensity ratio of the $2s\,^3S$–$np\,^3P$ He I series. The measured values of kT_e in both discharges were similar and lie between 0.07 and 0.11 eV. These low electron energies are typical of electric field free plasmas created by electron-beam excitation. At high electron densities and low metal vapor concentrations three-body recombination competes with charge transfer as the main loss channel of buffer gas ions in cw electron-beam pumped metal vapor lasers.

References

[1] J.J. Rocca, J.D. Meyer and G.J. Collins, Appl. Phys. Lett. 40 (1982) 300.
[2] J.J. Rocca, J.D. Meyer and G.J. Collins, Phys. Lett. 90A (1982) 358.
[3] J.J. Rocca, J.D. Meyer and G.J. Collins, IEEE J. Quantum Electron. 18 (1982) 1052.
[4] J.D. Meyer, J.J. Rocca, Z. Yu and G.J. Collins, IEEE J. Quantum Electron. 18 (1982) 326.
[5] J.J. Rocca, J. Meyer and G.J. Collins, Phys. Lett. 87A (1982) 237.
[6] J.J. Rocca, J. Meyer, Z. Yu, M. Farrell and G.J. Collins, Appl. Phys. Lett. 41 (1982) 811.
[7] Z. Yu, J.J. Rocca, J. Meyer and G.J. Collins, J. Appl. Phys. 53 (1982) 4704.
[8] G. Fetzer, J.J. Rocca and G.J. Collins, unpublished.
[9] L.R. Peterson, Phys. Rev. 187 (1965) 105.
[10] K.B. Persson, J. Appl. Phys. 36 (1965) 3086.
[11] C.B. Collins, A.S. Hicks, W.E. Wells and R. Burton, Phys. Rev. A6 (1972) 1545.
[12] J.M. Green, G.J. Collins and C.E. Webb, J. Phys. B6 (1973) 1545;
J.M. Green and C.E. Webb, J. Phys. B8 (1975) 1484.
[13] H.R. Griem, Phys. Rev. 131 (1963) 1170.
[14] B. Warner, Ph.D. dissertation, University of Colorado (1979).
[15] J.R. McNeil, Ph.D. dissertation, Colorado State University (1977).
[16] V.S. Aleinkov and V.V. Ushakov, Opt. Spectrosc. (USSR) 33 (1972) 116;
K. Kano, T. Shay and G.J. Collins, Appl. Phys. Lett. 27 (1975) 610.