and $I_2(\alpha) \simeq -2\alpha \int_0^{1-\Delta} dy\, y \sin(\nu \ln A)$

$$-2\alpha \int_{1-\Delta}^{1} dy\, e^{\pi\nu/2} y \sin(\nu \ln A)\,.$$

The second part is finite, but the first part diverges as $\alpha \propto (1/r) \to \infty$.

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[6]See, for example, H. Bethe and E. Salpeter, *Quantum Mechanics of One- and Two-Electron Systems* (Academic Press, Inc., New York, 1957).

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Measurements of the Stark Broadening of Two Neutral Helium Lines in a Plasma*

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(Received 4 March 1968)

A detailed study has been made of the broadening of the lines λ3889 Å (width only) and λ5016 Å (shift and width) of neutral helium in the plasma produced in an electromagnetically driven T tube operating in helium-hydrogen gas mixtures. The electron density in the plasma was found from the broadening of H_β, while the temperature was determined from the ratio of the intensity of H_β to that of the underlying continuum. Temperatures were in the range 20 000–30 000°K; electron densities varied from 10^{16} to 6×10^{17} cm^{-3}. The broadening of the line λ3889 Å was found to increase linearly with electron density; and it compared well with calculations based on the generalized impact theory, except for (constant) correction factors ranging from about 0.9 to 1.0 (depending on which of the various calculations is referred to). For the line λ5016 Å, neither of the previous calculations, nor a correction discussed here, predicts either the width or the shift variations satisfactorily; all the calculations give significantly wider lines above electron densities of 10^{17} cm^{-3} than are found experimentally. Also, as the electron density increases, the calculated shifts all become increasingly larger than those found experimentally. However, at the low densities most deviations are small ($\lesssim 20\%$).

INTRODUCTION

The Stark broadening of spectral lines by electrons and ions is a convenient and tried method of measuring the electron density in a plasma. This is particularly so for the hydrogen line H_β where the experimental ease of measuring only relative intensities in the visible spectrum is coupled with the existence of profile calculations that were estimated to be reliable to within ±15%.[1,2] Detailed comparisons[3] between theory and experiment[4] have since shown that these calculations may be reliable within ±4%, at an electron density of 2×10^{17} cm^{-3}; and the most recent experimental results[5] indicate that the absolute accuracy of the H_β calculations is ±3.5% in the range $(2 \leq N_e \leq 8)\times10^{16}$ cm^{-3}, all these errors being expressed in terms of H_β widths.

By comparison, the estimated accuracy of the first calculations of the broadening and shift of the lines of neutral helium[6] was only a little worse, being ±20% of the widths. Early experimental results[7] indicated that these calculations were at least as good as expected, but more recently[8,9] it has been suggested that the experimental results justify an empirical correction, namely that, on the average, the electron density calculated from the width of any neutral helium line should be increased by 10% to obtain the true value. In connection with such corrections there is considerable interest in improved calculations[10,11] of the broadening and shift of neutral helium lines, and there is a need for a more thorough experimental study. At the same time, the neutral helium lines, especially the strong ones like λ3889 Å, would be very useful as electron-density monitors. The line H_β is undoubtedly the best monitor for hydrogen and deuterium plasmas, and even for mixtures of hydrogen and helium; but if any other element is to be studied, the large number of lines emitted in the region of λ4800–5000 Å can make it very difficult to obtain a good profile of H_β. This is especially so at high electron densities when H_β is very broad ($\Delta\lambda_{1/2} \sim 50$ Å at $N_e = 10^{17}$ cm^{-3}). Under such conditions the neutral helium line λ3889 Å would be only 3 Å wide (full width), and thus has that much more chance of being unaffected by its neighbors.

For both of these reasons we have undertaken an extensive study of two lines of neutral helium, λ3889 Å and λ5016 Å. The stronger line λ5876 Å was not studied because it frequently becomes optically thick in our plasmas; the line λ3889 Å, on the other hand, is a strong line, but is still optically thin and isolated.

The weak hydrogen line H_ζ, which also has a wavelength of 3889 Å, is not a problem in this density range; for, at $N_e \sim 10^{16}$ cm^{-3}, its half-intensity width is approximately 90 Å compared with only ~0.3 Å for He I λ3889 Å, and at $N_e \sim 10^{17}$ cm^{-3}, it has already merged into the continuum. The line λ5016 Å is not very strong and is already close to H_β, but is interesting theoretically because the nearest perturbing level ($3d\,^1D$) is only 105 cm^{-1} from the upper level of the line.[12] Therefore this line is sensitive to Debye shielding[6] of the perturbing electrons even at moderate electron densities. For this investigation plasmas were created in various mixtures of helium and hydrogen in an electromagnetically driven T tube. The electron density was determined from the broadening of H_β, and the temperature from the ratio of the intensity of H_β to that of the underlying continuum.

APPARATUS

The T tube system used for these measurements was essentially the same as that used by Lincke and Griem.[9] A single 0.5-μF low-inductance capacitor was charged to a voltage in the range 30–40 kV, and then discharged through the pressurized spark gap and the T tube, which has the usual backstrap configuration.[13] The T tube was filled with a mixture of helium and hydrogen to a pressure between 0.75 and 3.5 Torr. To further vary the experimental conditions, helium-hydrogen (He:H_2) mixtures of 67:33, 80:20, 90:10, and 95:5 were used at different times. The filling gas was continuously pumped from the T tube. One monochromator was used to monitor the bremsstrahlung continuum at 2500 Å, which was taken as a reproducibility check, while a second monochromator (0.5 m Ebert-Fastie) aligned on the same optical path was used to scan on a shot-to-shot basis the profiles of H_β, He I λ3889 Å, and He I λ5016 Å. To cover as wide an electron density range as possible, the T tube was used with and without the shock reflector, and measurements were made at various times between 0.5 and 3.0 μsec behind the luminous front. Because of the rather rigid construction, the distance from the T-tube electrodes to the point of observation was fixed at 12 cm.

In striving for good reproducibility over a wide range of experimental conditions, it was found that the position of the reflector (when one was used) was critical. The reproducibility was further increased by not flushing the system between shots, presumably because the pressure remained more stable. No increase in the strength of impurity lines was observed which might have been caused by this change of procedure.

RESULTS

A typical set of measurements for a line profile consisted of three successive shots at each of 33 different wavelengths. An oscilloscope record showing three such measurements is reproduced in Fig. 1. In a few runs, profiles of H_β and both the helium lines were recorded, but more often only H_β and one of the helium lines. After each complete run, the bremsstrahlung monitor records were analyzed, and a mean value was found for each time of interest. Only those records were used for which the monitor signal at a given time was within ±5% of the mean value of the monitor signal at that time. With this selection process, 80% of the shots recorded were acceptable. A preliminary analysis[14] of the data for the line λ3889 Å using the half-widths as measured from this raw data, and with only an approximate evaluation of the temperature, showed already very small experimental uncertainties.

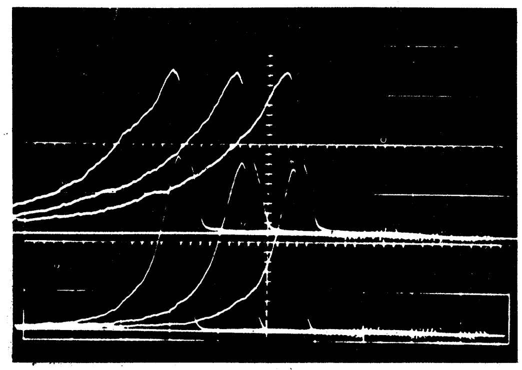

FIG. 1. Record of three successive shots of the T tube; top: continuum intensity at λ2500 Å; bottom: intensity of H_β plus continuum at λ4868 Å; Time scale: 1μ sec/division.

For all lines, great care was taken to insure that the photomultiplier and the amplifier were operating linearly by checking the system with calibrated neutral density filters. At high electron densities the H_β signals were corrected for changes in the sensitivity of the system with wavelength; however this correction was still less than 5% at 50 Å from the line center. For this correction, the complete optical system was calibrated against a tungsten ribbon lamp. The linearity of an individual wavelength scan was better than ±0.1 Å, and the shift of the line λ5016 Å was measured by direct comparison with the line λ5016 Å emitted by a helium-filled Osram lamp during the same wavelength scan.

The half-intensity widths of H_β were determined by graphically fitting the experimental profiles to the theoretical profiles.[2] In this way, a weighted average was taken of the red and blue wings (the red wing was frequently perturbed by the helium line λ4922 Å), and the proper values of the underlying continuum were readily found. The shape function $S(\alpha)$ of the H_β line (where α is the ratio of the wavelength in angstroms from the line center to the Holtsmark normal field strength) is very insensitive to both temperature and electron density. Therefore one needs very few theoretical profiles. For electron densities above 10^{17} cm^{-3}, the theoretical line shape at $N_e = 10^{17}$ cm^{-3} was used. To transform these half-intensity widths (full-widths $\Delta\lambda_{1/2}$) to electron densities, the tabulated broadening coefficients[15] of H$_\beta$ were used to calculate linewidths, and these theoretical linewidths were fitted to formulas of the type[16]

$$N_e = [\sum_j C_j (\log \Delta\lambda_{\frac{1}{2}})^j](\Delta\lambda_{\frac{1}{2}})^{\frac{3}{2}}. \quad (1)$$

Table I gives values of the coefficients C_j at various temperatures, including interpolated values for the temperature of 30 000°K. These formulas were used to calculate the electron density, assuming the plasma temperature to be both 20 000 and 30 000°K. Subsequently, when the plasma temperature had been determined (see below), the electron density was calculated by linear interpolation between the values for 20 000 and 30 000°K.

Table I. Stark broadening coefficients[a] for H$_\beta$ (Ref. 1). The index is the power of 10 by which the number must be multiplied.

Temperature (°K)	C_0	C_1	C_2	C_3
10 000	3.684^{14}	-1.430^{13}	-1.335^{12}	8.878^{10}
20 000	3.663^{14}	-1.284^{13}	-6.095^{12}	1.340^{12}
30 000	3.627^{14}	-1.225^{13}	-2.808^{12}	4.119^{11}
40 000	3.611^{14}	-1.419^{13}	-2.269^{12}	-8.960^{11}

[a]These coefficients differ somewhat from those given by Hill in Ref. 16, presumably because his formulas have been made to fit his interpolated values of $\Delta\lambda_{1/2}$ rather than values calculated directly from Ref. 15.

There are many ways of measuring the temperature of plasma,[17] but having already analyzed the H$_\beta$ profile to obtain the electron density, it was convenient to determine the temperature from the ratio of the intensity of H$_\beta$ to that of the underlying continuum. As this was not a pure hydrogen plasma, previous calculations[18] of this ratio were not applicable, and calculations had to be made of the ratio of Hβ to 100 Å of continuum for each of the helium-hydrogen mixtures used. This ratio is dependent on both the electron density and temperature, as shown in Fig. 2.

The half-intensity widths of the helium lines were also found by fitting the experimental points to theoretical profiles[6] by graphical procedures. However, these lines are asymmetric, and some care had to be exercised in choosing the correct line center (intensity maximum). In most cases, both the instrumental width and the Doppler width were negligibly small compared with the linewidth and could be neglected; only at the lower electron densities was some correction necessary. The instrument function was measured using the helium-filled Osram lamp, and found to be close to Gaussian in shape. The helium lines to be corrected were assumed to be Lorentzian, and use was made of the tabulation of Voigt profiles by Davies and

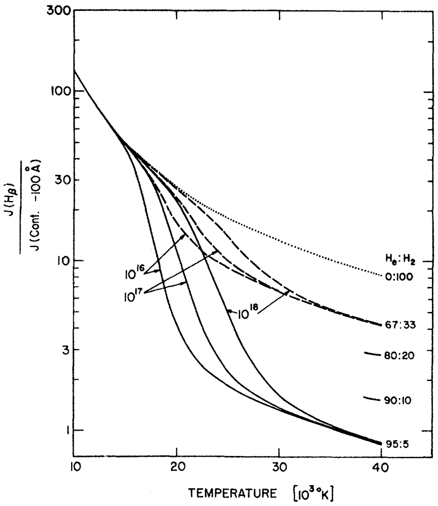

FIG. 2. The ratio of the total intensity of H$_\beta$ to the intensity of a 100 Å band of continuum centered at λ4861 Å as a function of temperature for various helium-hydrogen mixtures and electron densities of 10^{16}, 10^{17}, and 10^{18} cm^{-3}.

Vaughan.[19] In the worst case, the ratio of the measured linewidth to the instrument width plus Doppler width was 2.5. Thus the maximum correction was only 15%. Above electron densities of about 3×10^{16} cm^{-3} this correction was less than 2%.

The calculated broadening of the helium line λ3889 Å is very insensitive to temperature, there being less than 2% difference between the widths of the line at 20 000 and 30 000°K as long as Debye shielding is negligible (which is the case here). Therefore it was sufficient to approximate the plasma temperature to 20 000 or 30 000°K for the reduction of the data for this line. Electron densities were calculated from the half-intensity widths of λ3889 Å using the two theoretical results[6,10] available and the approximate formula[2]

$$w_{\text{total}} \simeq [1 + 1.75\alpha(1-0.75r)]w, \quad (2)$$

in which w is the electron-impact width, w_{total} is the total width due to both ions and electrons, α is the ion broadening parameter, and r is the ratio of the mean distance between ions and the Debye radius. The contribution to the total width from ion broadening was always less than ~20%. The original theory[6] (GBKO) is already in an analytical form (in regard to its electron-density dependence), but the tabulated values of w and α given by Oertel[10] had to be fitted to interpolation formulas. The results of these two interpretations are presented in Fig. 3 as the ratio of the electron density calculated from λ3889 Å to that calculated from H$_\beta$. Within the experimental error, it is seen that over the range 10^{16} cm$^{-3} \leq N_e \leq 6\times 10^{17}$ cm^{-3} the variation of the broadening of this line with electron density is very well described by both calculations. However, it is also clear that the older theory[6] gives an electron density which is on the average 9% lower[20] than that given by H$_\beta$, while the new calculation[10,11] agrees almost exactly with H$_\beta$.[21]

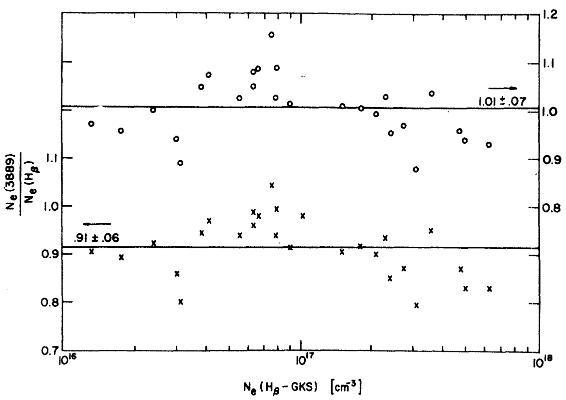

FIG. 3. The ratio of the electron density calculated from the helium line λ3889 Å to that calculated from H_β (Ref. 1, GKS) as a function of the electron density for both the GBKO (x-left scale) and Oertel (o-right scale) calculations. Solid lines represent the mean value of the respective data points.

The analysis of the data on the line λ5016 Å was more difficult because of the significant variation of the shift (d), width (w) and ion broadening parameter (α) with temperature. Again the GBKO theory[6] gives the electron-density dependence analytically, whereas, in order to account for this variation using the new calculations,[10] the tabulated values of these parameters were first interpolated to the experimentally measured temperature, then the total linewidth and shift predicted by the theory were computed for the electron density determined from H_β using Eq. (2) and the similar equation for the shift[2]

$$d_{\text{total}} \approx [(d/w) + 2.0\alpha(1-0.75r)]w. \tag{3}$$

In this case the maximum ion contribution to the total width was ~33%, and to the shift ~75%. At this extreme, the approximate formulas were both found to agree with the detailed profile calculations to within 2%. The results of this analysis[22] are presented in Figs. 4 and 5 as ratios of the width or shift of λ5016 Å calculated for the electron density given by H_β to the measured shift. This was done because there is clearly substantial disagreement between theory and experiment for λ5016 Å (in contrast to λ3889 Å); such a comparison therefore becomes more meaningful than a comparison of electron densities obtained from λ5016 Å and H_β. As can be seen, the experimental spread is a little larger than for λ3889 Å, and the agreement between theory and experiment is poor. A major difference between the old[6] and the new[10,11] calculations for λ5016 Å is the inclusion of the effect of Debye shielding in the new calculation. However, as suggested by Griem,[23] the effects of Debye shielding can, to a similar order of approximation, be allowed for by subtracting terms $a(\omega_{\alpha'\alpha}/\omega_p)$ and $b(\omega_{\alpha'\alpha}/\omega_p)$, respectively, from the real and imaginary parts of the second summation in the expression for $\langle\alpha|\Phi_a|\alpha\rangle$.[24]

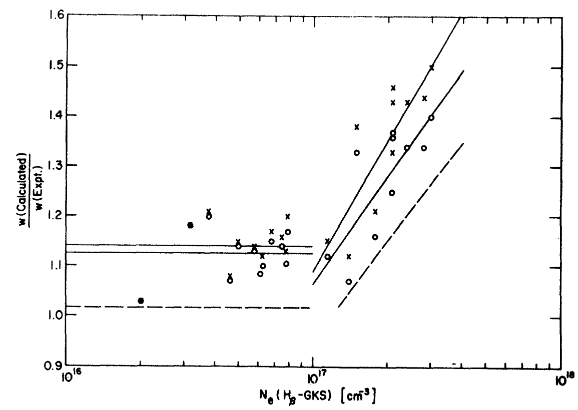

FIG. 4. The ratio of the width (w_{total}) calculated for the helium line λ5016 Å to that found experimentally as a function of the electron density determined from H_β (Ref. 1, GKS) : x, using GBKO calculation; o, using GBKO calculations with a correction for Debye shielding. Solid lines represent the mean value and least-squares linear fit of the respective data points. The dashed line represents the mean value and least-squares linear fit for the analysis using the Oertel calculation (the data points are not shown) .

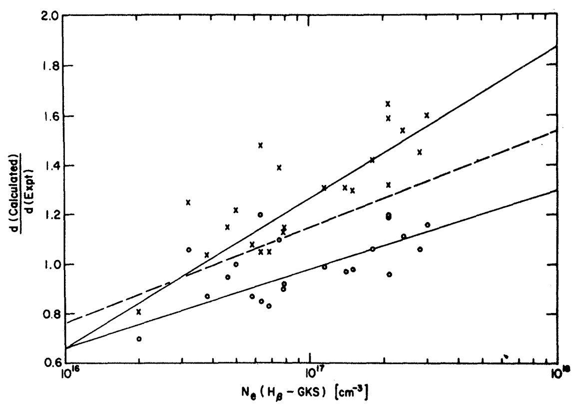

FIG. 5. The ratio of the shift (d_{total}) calculated for the helium line λ5016 Å to that found experimentally as a function of the electron density determined from H_β (Ref. 1, GKS) : x, using GBKO calculation; o, using GBKO calculation with a correction for Debye shielding. Solid lines represent the least-squares linear fit on the respective data points. The dashed line represents the least-squares linear fit for the analysis using the Oertel calculation (the data points are not shown) .

Making these subtractions results in a correction to the previously calculated width and shift given by

$$\Delta w = \frac{4}{3}\pi\left(\frac{2m}{\pi kT}\right)^{1/2}\left(\frac{\hbar}{m}\right)^2 \times \frac{10^{-8}\lambda^2}{2\pi c} N_e 67.5a\left(\frac{\omega_{\alpha'\alpha}}{\omega_p}\right), \tag{4}$$

and

$$\Delta d = \frac{4}{3}\pi\left(\frac{2m}{\pi kT}\right)^{1/2}\left(\frac{\hbar}{m}\right)^2 \times \frac{10^{-8}\lambda^2}{2\pi c} N_e 67.5b\left(\frac{\omega_{\alpha'\alpha}}{\omega_p}\right). \tag{5}$$

In these equations Δw, Δd, and λ are in angstrom units, and all symbols have their usual meaning (w is the half half-width). The functions $a(\omega_{a'a}/\omega_p)$ and $b(\omega_{a'a}/\omega_p)$ were interpolated from the tabulations given by Cooper and Oertel.[11] These corrections were applied to the GBKO calculations on λ5016 Å and are included in Figs. 4 and 5. The relevant perturbing level was taken to be $3d\,^1D\,(\omega_{\alpha'\alpha}=105\ \text{cm}^{-1})$.

DISCUSSION

Even under the worst conditions encountered in these measurements, i.e., highest electron density and lowest temperature, the optical depth at the center of the line λ3889 Å was calculated to be less than 0.04. Therefore no correction for bulk absorption was necessary. At the same time, reproducibility of the plasma conditions has already been assured. The problem of re-absorption in a cold boundary layer would have been most severe in the investigation of the neutral helium resonance line[9] in a similar helium-hydrogen plasma. However, even there it was found that absorption in the boundary layer was only ~ 20% at the center of the resonance line. Therefore, for the lines studied here, it is reasonable to assume that absorption in the boundary layer was much less than the experimental error. There remains the problem of inhomogeneity of the plasma itself. No direct measurement of the homogeneity of the plasma was made; however, the T-tube plasma is probably most inhomogeneous immediately behind the luminous front of the so-called "incident shock," and at long times after the creation of the "reflected shock," when a significant radial temperature distribution may be established. Line profiles were analyzed at different times from 0.5 to 3.0 μsec behind the luminous front in both the incident and reflected shocks, and no correlation was found between the deviation of theory from experiment and the time of observation.

Of the two lines studied, λ3889 Å is by far the better as an electron-density monitor. First its width is essentially independent of temperature; then it is a relatively strong line, narrow enough to be unaffected by its neighbors, yet wide enough to be easily measured. The experimental results obtained here can be summarized by the following equations,

$$N_e(3889\text{–GBKO})/N_e(\mathrm{H}_\beta)=0.91\pm0.06, \tag{6}$$

and

$$N_e(3889\text{–Oertel})/N_e(\mathrm{H}_\beta)=1.01\pm0.07, \tag{7}$$

for $10^{16}\ \text{cm}^{-3}<N_e<6\times10^{17}\ \text{cm}^{-3}$. In each case the error quoted is the standard deviation of the experimental measurements as defined, for instance, by Young,[25] and the GBKO factor would have to be increased by 4% if the tabulations of Ref. 6 were referred to (see Ref. 20). Because of the large number of measurements presented (27) and their reasonable adherence to a Gaussian distribution, it can be expected that the mean value of the ratio $N_e(3889)/N_e(\mathrm{H}_\beta)$ is within the standard deviation of the mean of the true value of this ratio.[25] Therefore the expected accuracy of this ratio when used as a correction factor in future experiments should be close to ±2%, except for the uncertainty in the broadening calculations of H_β. The above results substantiate the earlier suggestion[8,9] that an empirical correction of ~+10% should be applied to electron densities obtained using the GBKO calculations, as does the following result for λ5016 Å.

Below $N_e\sim10^{17}\ \text{cm}^{-3}$ the measurements of the width of λ5016 Å can be summarized by the equations

$$w(\text{GBKO})=(1.14\pm0.05)w(\text{experiment}), \tag{8}$$

and

$$w(\text{Oertel})=(1.02\pm0.04)w(\text{experiment}). \tag{9}$$

However, both the width and the shift of λ5016 Å above $N_e\sim10^{17}\ \text{cm}^{-3}$ deviate substantially from the calculated values (Figs. 4 and 5). The smoother variation of the ratio of "calculated to observed" shift with electron density can be understood in part by remembering that Debye shielding effects become numerically important[10,11] in the shift calculation at $N_e\approx10^{16}\ \text{cm}^{-3}$, whereas in the width calculation they become important only above $N_e\approx10^{17}\ \text{cm}^{-3}$. Furthermore, the shift of λ5016 Å is dominated over the whole range of electron densities by the ion contribution, in which Debye shielding has already been accounted for.[6] Since for both shift and width of λ5016 Å the ratio of "calculated to observed" increases with increasing electron density, while for λ3889 Å the ratio is essentially constant, one might be tempted to assume that the present estimates of the effect of Debye shielding are too low. However, it seems unlikely that a more detailed evaluation of Debye shielding effects would lead to sufficiently decreased widths and shifts, as to account for all of the observed discrepancies.

ACKNOWLEDGMENTS

The authors are indebted to J. Cooper and G. K. Oertel for providing preprints of their papers. They also thank P. Kepple for providing preliminary data from his new calculation on the broadening of H_β. One of us (C.P.L.) was on overseas study leave from the University of Malaya and thanks the Fulbright Conference Board Committee for a Fulbright Scholarship.

*Jointly supported by the National Aeronautics and Space Administration and National Science Foundation.

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[20]Actually, results for the GBKO calculation were taken from Ref. 2; for the width of λ3889 Å the difference between these two tabulations (Ref. 6 and Ref. 2) is ~4% and would increase $N_e(3889)$; i.e., the mean value of $N_e(3889)/N_e(H_\beta)$ becomes $N_e(3889\text{–GBKO})/N_e(H_\beta) = 0.95 \pm 0.06$.

[21]A more refined calculation of the broadening of the lower members of the Balmer series is now in process. [P. Kepple, Bull. Am. Phys. Soc. 13, 265 (1968); P. Kepple and Hans R. Griem, to be published]. Preliminary results indicate that the electron density determined from H_β is changed by ~1% which is clearly negligible.

[22]Again the results for the GBKO calculation were taken from Ref. 2. Now, however, the difference between the two tabulations is negligible compared with the experimental errors for the width of λ5016 Å, but it increases the shift by 16% at $N_e = 10^{18}$ cm^{-3} and 43% at $N_e = 10^{16}$ cm^{-3}. Therefore the slopes of the lines drawn in Fig. 5 remain unchanged but the intercept becomes 0.94 instead of 0.66 at $N_e = 10^{16}$ cm^{-3}.

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Energy Distribution Function for Helium*

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(Received 2 October 1967)

The energy distribution functions, electron mean energies, drift velocities, and electron temperatures are calculated for several values of E/P: 0.1, 0.2, 0.3, ...1 and 2, 3, 4, ...10, where the strength E of the applied electric field is given in V/cm and the pressure P of the gas in Torr. The effects of elastic scattering only are considered. The calculations are carried out for helium using the available data for the momentum-transfer cross sections $Q_D(\epsilon)$, where ϵ is the electron energy in eV. The results are strongly dependent on these data. The assumption that Q_D is constant for intermediate values of $\epsilon > 19.2$ eV, proposed by Barbière, is apparently in serious error, particularly for $E/P > 3$ V/cm Torr. Using the phase-shift data of McDougall, Allis and Morse, and of LaBahn and Callaway, the values of $Q_D(\epsilon)$ at intermediate and high electron energies vary as $1/\epsilon^n$, where n lies between $\frac{3}{4}$ and $\frac{7}{8}$. In this case the distribution functions converge slowly, and the calculated drift velocities are much higher than those obtained from experiment. With $Q_D \propto 1/\epsilon^{1/2}$ for $\epsilon > 40$ eV, the recent data of Frost and Phelps for the momentum-transfer cross sections give the best agreement with experiment. The calculated drift velocities are lower than those measured. By assuming $Q_D \propto 1/\epsilon^{1/2}$ for $\epsilon > 19.2$ eV and considering the experimental data of Ramsauer and Kollath for the differential scattering cross sections and the data given recently by Golden and Bandel for the total scattering cross sections, good agreement is found for the calculated drift velocities. In this case, the calculated values are higher than those observed. The experimental data of Crompton and Jory for the momentum-transfer cross sections do not offer satisfactory values for the drift velocities; the higher the values of E/P, the less the agreement between calculations and the experimental results.

I. INTRODUCTION

The study of the energy distribution functions in gas discharges and slightly ionized gases is of particular interest.[1] It is of considerable importance to know the distribution function as accurately as possible. Different theories including both elastic and inelastic collisions have been developed.[2,3] In the case of elastic collisions, an exact solution has been attained.[4] The problem is strongly dependent on the momentum-transfer cross sections $Q_D(\epsilon)$, where ϵ is the electron energy in eV. Using the Ramsauer and Kollath[5] swarm-technique data for helium, Barbière[6] calculated the energy distribution, drift velocity,

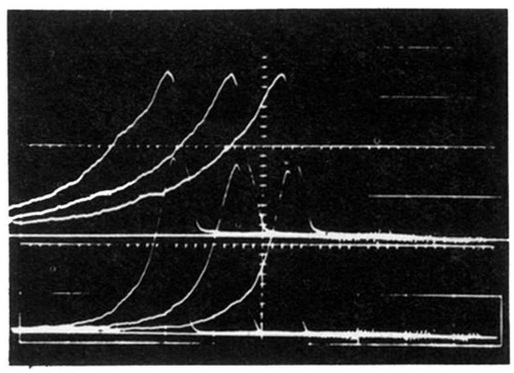

FIG. 1. Record of three successive shots of the T tube; top: continuum intensity at λ2500 Å; bottom: intensity of H_β plus continuum at λ4868 Å; Time scale: 1μ sec/division.