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A SPECTROSCOPIC DETERMINATION OF ELECTRON TEMPERATURE IN A HIGH TEMPERATURE PLASMA

by

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ABSTRACT

The electron temperature of a high temperature plasma is determined by measuring the intensity ratio of the 2s-2p and 2s-3p transitions in the same Li-like ion. The theoretical dependance of the intensity ratio of electron temperature is given for several Li-like ions between CIV and SiXII. It is assumed that the free electrons have a Maxwellian distribution of velocities and that the distribution of electron populations over the bound levels is given by a coronal type equation. A collisional excitation cross-section derived by Seaton is used. The use of spectral lines emitted by the same ion and with a common lower level gives an intensity ratio that is a function of electron temperature only and free from several ambiguities which may arise from spatial and temporal variations. The method can be used for measurements of electron temperature between about 5 eV and 200 eV.

This method has been used to determine the electron temperature of the pulsed deuterium plasma in ZETA over a wide range of conditions by measuring the intensity ratio of the NV 1238.8 Å and 209.3 Å lines photoelectrically with a grazing-incidence monochromator. A relative photometric calibration was obtained, firstly from the known relative photoelectric yield of a tungsten reference cathode, and secondly by using the branching ratio method with the HeII ion. The errors in the measurement of electron temperature arising from random and systematic errors in the measurement of the intensity ratio are also discussed.

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1. INTRODUCTION

Spectroscopic methods for measuring the temperature of a plasma in thermodynamic equilibrium are well established. For these plasmas, the distribution of electron populations over the bound and free states and the distribution of ion species are given by the Boltzmann and Saha equations. The dependence of the spectral radiation from the plasma on temperature can be calculated, and an analysis of the radiation will establish the temperature of the plasma.

However, the high temperature plasmas produced in the laboratory for controlled thermonuclear research are usually far removed from thermodynamic equilibrium. This is also true of some astronomical plasmas, for example, the solar corona and chromosphere. Such plasmas, in which the complete distribution of electron populations over bound or free states depart significantly from Boltzmann and Saha distributions, will be termed 'non-thermal'. In such cases, the complete distribution of electron populations and the distribution of ion species can only be determined by a consideration of the detailed atomic processes controlling excitation and ionization. Usually, however, the free electrons will approximate to a Maxwellian velocity distribution characterised by an electron temperature T_e, and the intensity distribution of the continuum radiation due to free-free (bremstrahlung) and free-bound (recombination) transitions can then be calculated using thermal equations and analysed to yield a valid measurement of electron temperature. Jahoda et al. (1960) have measured the electron temperature of a Scylla discharge by analysing the shape of the continuous radiation in the X-ray region of the spectrum near the high frequency limit. McWhirter (1963) has described a method of measuring the electron temperature of a hydrogen plasma by measuring the intensity ratio of the recombination radiation and bremsstrahlung radiation on both sides of the Balmer or Lyman steps.

The intensity of the continuous radiation from a low density non-thermal plasma often is too low for accurate measurements, and in addition, the spectrum usually is complicated by emission lines from highly ionized impurity ions. Because this line radiation is intense, it is much more easily distinguished from its background but its use as a measurement of electron temperature is complicated by difficulties of interpretation. However, high temperature plasmas are usually in a domain of electron density and temperature where radiative decay rates predominate over collision induced decay rates. In this situation, the steady state excitation and ionization populations reduce to simple equations which were derived by Woolley and Allen (1948) to explain the spectrum of the solar corona. These equations have been used to determine the electron temperature of the corona from observa-

tions of the relative strengths of spectral lines emitted by different ions, e.g. Fe X/Fe XIV (de Jager, 1955).

Apart from uncertainties in the cross-sections, this method is also subject to uncertainties due to possible spatial variations in the line of sight. This is also true of high temperature laboratory plasmas, but a much more serious objection, which prevents the use of the method, is that the system is generally not in a steady state so that the ionization distribution at any time can only be determined by a transient solution of the basic equations. Further, since successive ionization stages appear at different times, considerable uncertainties are introduced due to possible temporal variations in the plasma. Thus the use of line intensities to determine electron temperature in high temperature laboratory plasmas is much more reliable if the measurements are limited to spectral lines emitted by the same ion.

Two such methods have been used. Firstly, Cunningham (1955) has used the intensity ratio of the singlet and triplet lines of HeI at 4921 Å and 4713 Å assuming the excitation to be coronal in nature (solely by electron impact from the ground state). Since the collisional cross-sections have a quite different dependence on electron energy, this ratio is a function of electron temperature. The assumption of a coronal excitation is very suspect, however, because of the effect of the high lying metastable levels 2^1S and 2^3S and is probably valid only at very low densities (less than about 10^{10} cm^{-3}). Secondly, the absolute intensity of the CV line $2^3S_1 - 2^3P_2$ at 2271 Å has been used to give a rough estimate of electron temperature in the high current-pinch discharge of ZETA (Butt et al. 1958, Burton et al. 1961). This method has been refined and developed by Williams and Kaufman (1960). This line of CV falls at a wavelength where a measurement of the absolute photometric calibration of a spectrograph can be made, but the method also requires estimates of the densities of electrons and CV ions in the line of sight, which are subject to considerable uncertainties. However, because the line originated from a high level in the ion (304 eV above the groundstate) and its intensity is therefore particularly sensitive to electron temperature in the range 20–40 eV, the method should be valid within this range of electron temperature. A more detailed account of existing spectroscopic methods for measuring ultra high temperatures and their limitations is given by Thonemann (1961).

This paper presents a new method of determining electron temperature based on the measurement of the intensity ratio of spectral lines emitted by the same ion and with a common lower level. To obtain a ratio which is sensitive to temperature, it is necessary that the upper levels be well separated in energy. The 2s-2p and 2s-3p transitions of the Li-like ions are particularly convenient for this purpose. The theoretical expression for

this ratio is developed assuming a Maxwellian distribution of electron velocities and an excitation distribution given by coronal type equations. The former assumption will depend on the particular plasma and should be examined in each individual case. The latter assumption will be generally true for Li-like ions, which have no metastable states, in high temperature plasmas where the excitation distribution will reach a quasi-steady state with the ground level even if the ionization is transient in character.

The theoretical ratios are independent of electron density and are a unique function of electron temperature. The main theoretical uncertainty is due to uncertainties in the cross-section for excitation by electron impact especially as these are theoretical values, supported only rather indirectly by experiment (Seaton 1962). The method is potentially very powerful and will embrace a range of about 5 eV to 200 eV if the required observations are available for the Li-like sequence CIV to Si XII. However, the method presents a difficult experimental problem associated with the measurement of the relative intensities of spectral lines of widely different wavelength in the extreme ultra-violet and soft X-ray region of the spectrum.

The experimental application of the method was carried out on the high temperature pulsed plasma produced in ZETA. Line intensities were measured photo-electrically using a grazing-incidence rocket monochromator (Hinteregger 1961) on loan from the Geophysics Research Directorate (GRD). This instrument has been used extensively to measure the monochromatic solar flux from rockets (Hinteregger 1961) and has been adapted for laboratory use on pulsed plasmas. It covers the wavelength range 57 Å to 1250 Å and was calibrated over part of this wavelength range at GRD using a tungsten reference cathode (Hinteregger et al. 1960, Hinteregger 1961). This calibration was combined with the branching ratio method (Griffin and McWhirter 1962) which was applied using the HeII ion to give a resulting calibration over the wavelength range 237 Å - 1250 Å. Since NV is the only Li-like ion for which the relevant transitions (t 209.3 Å and 1238.8 Å) lie within or near this range of calibration, the present measurements are limited to this ion. The theoretical calculations of the line intensity ratios of Li-like ions, however, are given for several ions. An experimental application of the method to ions other than NV is dependent upon an extension of the photometric calibration of the monochromator.

2. THEORETICAL

2.1 Excitation Populations

In general, the distribution of electron populations over bound and free states will

depend on the detailed parameters of the plasma such as density, composition, and temperature, and on the method of heating and confinement. The types of distribution have been reviewed by Wilson (1962) and can vary considerably. However, the high temperature plasma is usually in a domain where the excitation populations are given by the simple coronal type equations. Thus, the population densities n_q of the qth excited state relative to the ground state n_1 is given by

$$n_q/n_1 = n_e S_{1q}/A_q \ , \qquad \ldots (1)$$

where n_e is the electron number density (cm^{-3}), S_{1q} is the collisional excitation function ($cm^3\ sec^{-1}$) and A_q is the total Einstein transition probability (sec^{-1}) for level q.

An approximate criterion for this equation to be valid for all excited levels which carry a significant population is given by Wilson (1962) as

$$n_e \leqslant 1.5 \times 10^{10}\ \chi_i^{-\frac{1}{2}}\ (kT_e)^4 \ , \qquad \ldots (2)$$

where the ionization potential χ_i of the ion being considered and the electron temperature kT_e are in eV. Wilson also describes a 'semi-coronal' domain where equation (1) is valid except for levels near the ionization limit. Since we are not concerned in this paper with such high lying levels, this domain represents a more realistic and less stringent criterion for the application of the following theory. The criterion for the semi-coronal domain is given by Wilson (1962) as

$$n_e \leqslant 10^{11}\ \chi_i^{\frac{3}{2}}\ (kT_e)^2 \ . \qquad \ldots (3)$$

Equation (3) is valid only for ions without metastable levels.

An additional condition for the validity of equation (1) is that the line radiation emitted by the ion should be optically thin. The criterion for this to be so is $\tau_o \leqslant 2\sqrt{2}/10$ (Burton and Wilson 1961), where τ_o is the optical depth at the central frequency of the line. This reduces to

$$Dn_1 \leqslant 20\ \Delta\upsilon_D/f \ , \qquad \ldots (4)$$

where D is the depth of the plasma in the line of sight, n_1 the population density of the ground state, $\Delta\upsilon_D$ the Doppler half width in frequency units, and f the absorption oscillator strength. This criterion was obtained assuming a Boltzmann distribution among the excited states. Recent work by Hearn (1963) on radiative transfer in spectral lines shows that the criterion of equation (4) is considerably relaxed (by about an order of magnitude) when distributions are of the form given by equation (1).

In high temperature pulsed plasmas, the observed spectra are usually of a transient nature and the populations n_1 and n_q vary with time in a complicated fashion. However,

equation (1) will still be valid and will represent a quasi-steady since the relaxation time for the excited state to come into equilibrium with the ground state is $1/A_q$ which is of the order of 10^{-8} sec.

2.2 Ratio of Line Intensities for Li-like Ions

The transitions used are $2s^2S_{1/2} - 2p^2P^o_{3/2}$ and $2s^2S_{1/2} - 3p^2P^o_{1/2,3/2}$; they are indicated in the partial energy level diagram given in Fig.1. Both components of the latter multiplet are used since these will be difficult to resolve in practice. The populations within each multiplet are distributed according to their statistical weights.

Using equation (1) the intensity ratio of these transitions is given by

$$\frac{I(2s^2S_{1/2} - 2p^2P^o_{3/2})}{I(2s^2S_{1/2} - 3p^2P^o_{1/2,3/2})} = \frac{I_{1q}}{I_{1r}} = \frac{S_{1q}\, A_{1q}/A_q}{S_{1r}\, A_{1r}/A_r} , \qquad \ldots (5)$$

where A_{1q} is the transition probability for the particular line and A_q the total transition probability for the upper level. Since the only possible transition for the 2p configuration is to the ground state, A_{1q}/A_q is equal to unity. The corresponding factor for the 2s - 3p transition is also equal to unity to within one percent because the transition probability for the 3s - 3p transition is relatively small (Allen 1955). The intensity ratio therefore becomes

$$I_{1q}/I_{1r} = S_{1q}/S_{1r} . \qquad \ldots (6)$$

The collisional excitation functions S_{1q} are obtained from the relevant cross sections. In terms of the 1-q excitation transition,

$$S_{1q} = \int_{\upsilon_{1q}}^{\infty} Q_{1q}(\upsilon)\ f(\upsilon)\, d\upsilon ,$$

where $Q_{1q}(\upsilon)$ is the cross section for excitation by electrons of velocity υ, υ_{1q} is the velocity corresponding to the excitation energy of state q, and $f(\upsilon)$ is the electron velocity distribution, the ion velocity being negligible. The conditions for $f(\upsilon)$ to be a Maxwellian distribution have been considered by Thonemann (1961) and Wilson (1962) and depend on the electron-electron relaxation time (Spitzer 1956) being short compared to the characteristic times of heating and confinement. Although this should be examined carefully in each individual case, it will be assumed here that the distribution is Maxwellian.

Collisional excitation cross sections for bound-bound transitions have been measured for only a few transitions in simple atomic systems. Calculated cross sections, based on the Born approximation, give good results for electron energies several orders of magnitude above the threshold energy of the transition, but usually over estimate the cross section

for electron energies near threshold. For the range of electron energies encountered in laboratory plasmas, the behaviour of the cross section near threshold is important. The values adopted here are due to Seaton (1962) who has recently derived an approximate expression for the collisional excitation cross section of optically allowed transitions in positive ions using a Born-Coulomb treatment. Seaton's method requires only a knowledge of the absorption oscillator strength f and includes a mean Kramers-Gaunt function $\bar{g}$ which depends somewhat on the magnitude of electron energy above threshold. When this cross section is averaged over a Maxwellian distribution of electron velocities of temperature T_e, the excitation function S_{1q} becomes (see Allen 1963)

$$S_{1q} = \frac{1.6 \times 10^{-5} f_{1q} \bar{g}(\chi_{1q}/kT_e)}{\chi_{1q}(kT_e)^{\frac{1}{2}}} \exp(-\chi_{1q}/kT_e). \qquad \ldots (7)$$

In this equation f_{1q} is the absorption oscillator strength for the transition, χ_{1q} is the energy of level q above the ground state, and χ_{1q} and kT_e are in eV.

When the intensity ratio of a pair of emission lines from the same ion is considered, only the relative magnitude of the collisional excitation functions will be important so that uncertainties in their absolute magnitudes should tend to cancel. Using the Seaton excitation function (equation (7)) in equation (6), the relative intensity of the lines being considered becomes

$$\frac{I(2s^2S_{1/2} - 2p^2P^o_{3/2})}{I(2s^2S_{1/2} - 3p^2P^o_{1/2,3/2})} = \frac{I_{1q}}{I_{1r}} = \frac{f_{1q}\chi_{1r}\bar{g}(\chi_{1q}/kT_e)}{f_{1r}\chi_{1q}\bar{g}(\chi_{1r}/kT_e)} \exp\frac{\chi_{1r} - \chi_{1q}}{kT_e} \qquad \ldots (8)$$

Values of this ratio calculated for several Li-like ions between CIV and SiXII are plotted as a function of electron temperature in Fig.2, and the important atomic parameters for the relevant transitions are listed in Table I. The function $\bar{g}(\chi/kT_e)$ is tabulated by Allen (1963) and is calculated by using theoretical estimates near threshold and experimental values for atoms above threshold (Seaton 1962). The transition integrals σ^2, the absorption oscillator strengths f of the component lines, and the transition probabilities A were calculated using the Coulomb approximation of Bates and Damgaard (1942). The data for several of these transitions were taken from tables compiled by Allen (1955), and the remainder were calculated for the present problem. With the exception of the NeVIII resonance doublet, which was measured only recently in the ZETA apparatus by Fawcett, Jones and Wilson (1961), the wavelengths of the transitions were obtained either from tables by Moore (1949) or by an isoelectronic extrapolation using these tables.

3. EXPERIMENTAL

3.1 Experimental Technique

Measurements of electron temperature were made of the deuterium plasma in ZETA, the high temperature pinch discharge, described by Butt et al. (1958) and Burton et al. (1961). The deuterium gas pressure within the torus of ZETA was varied between ½ to 2 mTorr, and a trace of nitrogen, amounting to about 1% of the deuterium concentration, was added to the discharge for spectroscopic observations. The voltage applied to the capacitor bank, which had a stored energy capability of 3 MJ at 24 kV, was varied over the range 5 kV to 20 kV. The discharge was operated in about 45 second intervals, and the duration of the current pulse was about 3 m sec. Peak values of the gas current ranged between 250 kA to 600 kA.

Spectroscopic measurements were made with a 2 meter grazing-incidence monochromator employing photoelectric detection. Fig.3 gives a schematic illustration of the monochromator, and also indicates the coupling of the monochromator to ZETA. Except for modifications in the electronic circuitry and in the wavelength scanning drive, the instrument is identical to the rocket monochromator described by Hinteregger et al. (1960) and in greater detail by Hinteregger (1961).

A Bendix magnetic photomultiplier (Heroux and Hinteregger 1960) with a 3.5 in. long cathode intercepted the dispersed radiation which passed through the exit slit. The width of the entrance slit was 25 micron and its length 8 mm. The width of the exit slit was selected to accept the entire profile of the emission line. The resolution of the monochromator near the centre of its wavelength range was about 1 Å.

The monochromator was positioned accurately, with removable dowelling pins, in a stainless steel vacuum chamber so that a radial view of the plasma was obtained. Except for communication through the entrance slit of the monochromator, the torus and vacuum chamber were completely isolated. A 4 in. oil diffusion pump and liquid nitrogen trap, mounted on the vacuum chamber, produced a typical operating pressure of about 10^{-5} Torr. A variable speed motor mounted outside the vacuum chamber was coupled to the belt drive of the monochromator through a rotary vacuum seal. The motor drive and a synchro-indicator permitted remote wavelength scanning.

The photomultiplier was operated so that the temporal variation in anode current could be measured. The cathode of the photomultiplier was operated near ground potential and the anode at positive high voltage. A potential of about 30 V was applied to the resistance strip cathode to produce a nearly uniform response along the length of the cathode. The anode current was passed through a 100 kΩ load resistor, and the anode voltage signal

was capacitively coupled to a balanced amplifier which rejected in-phase pick-up signals. The time constant of the anode circuit and the frequency response of the amplifier were selected so that the transient anode signal associated with the emission lines was not distorted.

The anode signal of the photomultiplier and the current waveform of ZETA were photographed simultaneously for each discharge. Time markers were superimposed on all signal traces, and amplitude markers were displayed occasionally immediately following the current pulse of ZETA. For fixed experimental conditions and a particular emission line, the variation in peak amplitude of the anode signal for different discharges is about ± 50%. For relative measurements of a pair of emission lines, measurements on each line were made alternately in groups of ten until at least forty measurements were accumulated for each line. The random error in the ratio of the anode signals is therefore about ± 10%.

3.2 Relative Photometric Calibration of the Monochromator

To calibrate the monochromator using a reference tungsten cathode, the photomultiplier was operated as a photo-electron counter in the region of its counting plateau (Heroux and Hinteregger 1960) and the instrument illuminated with monochromatic radiation at several wavelengths between 256 Å and 1216 Å. The transmission of the instrument for a particular wavelength was obtained from the ratio of the counting rate of the monochromator to the rate of emission of photo-electrons from an untreated tungsten cathode that could be inserted between the entrance slit of the monochromator and grating to intercept all radiation falling on the grating. A slight extrapolation was also used to extend the transmission measurement from 1216 Å to 1239 Å. The measurement of transmission was combined with the known photoelectric yield of the cathode between 470 Å and 1239 Å (Weissler 1956) to provide an approximate absolute photometric calibration of the instrument over this range of wavelengths. The photo-electric yield of the cathode for wavelengths between 256 Å and 460 Å was estimated from measurements near 460 Å (Weissler 1956) and a single measurement at 113 Å (Lukirskii et al. 1960); therefore, only a crude calibration was possible for the wavelength range 256 Å - 470 Å.

Errors in the photo-electric yield of tungsten introduce errors in the absolute photometric calibration of the instrument. In addition, the accuracy of an absolute calibration will depend on the degree of polarization of the incident monochromatic beam used for calibration and on the method of illuminating the entrance aperture of the astigmatic instrument. When only a relative photometric calibration over a small wavelength range is required, the errors are probably considerably reduced. For the measurements of electron

temperature described here, the relative calibration obtained with the reference tungsten cathode was used only over the limited wavelength range 1085 Å - 1239 Å. Over this range, the relative values of the photo-electric yield are probably good to ± 10%. Also, for a relative calibration, only the variation in the degree of polarization of the incident monochromatic beam used for calibration is important. Since the monochromatic radiation was derived from an additional laboratory grating monochromator, which will not produce a significant change in the degree of polarization over the range of wavelengths used, the influence of the polarization of the monochromatic beam on the relative spectral calibration will be negligible. Errors in the relative calibration for the range 1085 Å - 1239 Å arising from astigmatism also will be small and are estimated to be about ± 10%. The approximate relative calibration of the instrument over the large wavelength range 256 Å - 1085 Å was used only as a guide to extrapolate the branching ratio measurement of calibration at 237 Å to 209 Å (see below).

For measurements on ZETA, the magnetic photomultiplier was not operated as a photo-electron counter, but in a conventional d.c. fashion where the amplitude of the anode signal depends on the photomultiplier gain. Because the collection efficiency of photo-electrons emitted at different sections along the length of the cathode varies slightly with photomultiplier gain, the relative spectral calibration of the instrument also will vary slightly with gain. These variations in cathode sensitivity were investigated for the range of gains used for measurements on ZETA and were considered in analysing the data.

The relative photometric calibration of the monochromator was extended from 1085 Å to 236 Å by applying the branching ratio technique to selected emission lines of the HeII ion which was excited in the ZETA discharge. This method was used previously with hydrogen by Griffin and McWhirter (1962) to obtain an absolute intensity calibration at 1025 Å. The method consists of measuring the intensity ratio of two emission lines that originate from a common upper level for which the transition probabilities are known. If the line radiation is optically thin, the theoretical ratio of the line intensities will depend only on the ratio of their transition probabilities and not on the mechanism of excitation of the upper level. For a hydrogen-like system, the transition probabilities are known precisely; therefore, an experimental measurement of the intensity ratio of the pair of emission lines will yield a relative calibration of the monochromator at two wavelengths.

Two emission lines of HeII from the common upper level $n = 5$ to the ground state $n = 1$ (237 Å) and to $n = 2$ (1085 Å) were selected for analysis. The transitions between $n = 4$ to $n = 1$ (1216 Å) and to $n = 2$ (247 Å) also fall within the instrumental wavelength,

but could not be used because of interference from hydrogen L_α (1216 Å). The transition probabilities (Allen 1955, Bethe and Salpeter 1957) of the selected lines give their optically thin intensity ratio as I(237 Å)/I(1085 Å) = 1.63. This procedure is valid only if the sub-levels within the principal level (n = 5) are populated according to their statistical weights. For the range of electron temperatures and densities in ZETA, collisional processes between the closely spaced sub-levels will ensure that this condition is satisfied (Griffin and McWhirter 1962).

Experimental measurements of the intensity ratio for the two lines of HeII were obtained by operating the ZETA discharge in helium. Measurements were made for helium pressures of 1/4, 1/2 and 1 m torr and their ratio found to be the same, within the limits of experimental error (± 10%). A constant ratio with varying gas pressure indicated that there was no appreciable re-absorption of the emission line that terminates on level n = 1 (237 Å). This supports the theoretical estimate that the optical depth in the centre of this line is 0.1 for a 1/2 mTorr filling pressure and an assumed ion temperature of 100 eV. This experimental measurement of the intensity ratio was combined with its theoretical value to obtain a relative calibration of the monochromator at 1085 Å and 237 Å. The previous sources of error due to astigmatism, polarization, and measurements of the photo-electric yield of tungsten are not introduced when the monochromator is calibrated on ZETA using the branching ratio method. The only error in the relative calibration between 1085 Å and 237 Å, assuming optical thinness, arises from the random variation in the intensity of the HeII emission lines for different discharges. This error was also about ± 10% (see section 3.1).

To obtain a relative photometric calibration of the instrument for the relevant lines of the NV ion at 1238.8 Å, and 209.3 Å, the relative calibrations over the wavelength range 1085 Å - 1239 Å (tungsten cathode) and for the two wavelengths 1085 Å and 237 Å (branching ratio method) were combined. This slight extrapolation in calibration from 237 Å to 209 Å was carried out using the tungsten cathode calibration between 256 Å to 1085 Å. The total error in the relative calibration of the monochromator for the relevant lines of the NV ion was estimated to be ± 25%.

4. RESULTS

4.1 Measurements of T_e on ZETA using the NV Ion

The intensity ratio of the NV emission lines $2s^2S_{1/2} - 2p^2P^o_{3/2}$ (1238.8 Å) and $2s^2S_{1/2} - 3p^2P^o_{1/2,3/2}$ (209.3 Å) were measured and their ratio converted to electron

temperature using the appropriate curve of Fig.2. The temporal variation of the emission lines of highly ionized ions in the deuterium plasma of ZETA has been studied by Burton and Wilson (1961). In general, the intensity-time profile of an emission line consists of an initial transient followed by an injection tail that depends upon the value of the axial stabilizing field B_z. The peak intensity of the transient for lithium-like ions above ionization state III occurs after the initial deuterium ionization phase is complete. All data on electron temperature presented here were obtained from measurements at the peak of the intensity transients of the two emission lines.

Typical line intensity trace of the NV ion are shown in Fig.4 for a particular discharge condition where the stabilizing field B_z was adjusted so that only the initial transient of the emission line appears. The time of appearance of the transient after the initiation of the current pulse depends on the discharge conditions. For a fixed discharge condition, the time of appearance of the transient for a group of discharges is reproducible to about ± 5 μsec. The transient of the 209.3 Å line occurs about 30 μsec later than that of the 1238.8 Å line. This time interval was observed for a wide range of discharge conditions, and because it corresponds to a gas current change of only a few per cent, it will not be of significance in the measurement of electron temperature. It can be explained by a slight gradient in temperature since an increase of about 0.1 eV in kT_e during the 30 μsec interval is sufficient to explain the discrepancy. For the parameters of ZETA in Fig.4, this gives a very rough temperature-current gradient (near 200 kA) of about 0.012 eV/kA. Measurements of electron temperature at times during the transient other than at the peak of the transients were not practical because of variations in the shape of the transient for different discharges. The measurement of electron temperature presented here refers only to the specific time and value of gas current corresponding to the peak of the transients. This restriction in the time of measurement of electron temperature can be overcome in the future by using other ions of the lithium-like sequence which appear at different times during the discharge.

Measurements of electron temperature in ZETA for several values of the magnetic parameter θ and for a constant gas pressure and capacitor bank voltage are presented in Fig.5. The magnetic parameter θ (Lees and Rusbridge 1959) is related to B_z and is defined as $\theta = 2I/aB_z$, where I is the peak value of gas current, a is the minor radius of the torus, and B_z is the initial value of the axial stabilizing magnetic field. The initial transient occurs at approximately the same time before peak current for the entire range of θ. One discharge condition ($\theta = 2.0$) corresponds to the illustration of Fig.4. A large injection tail near peak gas current appears for both emission lines for $\theta = 4.0$

(Burton and Wilson 1961). The peaks of the transients, however, occur before the injection tail is significant. It is apparent from Fig.5 that the electron temperature measured at about 2/3 peak gas current (see Fig.4) does not vary appreciably with the magnetic parameter θ.

Fig.6 presents measurements of the electron temperature for four values of capacitor bank voltage between 5 kV and 20 kV and for constant values of the magnetic parameter θ (2.0) and gas pressure (0.5 mTorr). The electron temperature is plotted against the value of gas current at the time of measurement. The peak value of gas current increased linearly with capacitor bank voltage from 150 kA at 5 kV to about 600 kA at 20 kV. Therefore, the measurement of electron temperature for a capacitor bank voltage of 5 kV was obtained near peak gas current, while for 20 kV, the measurement was made considerably below the peak value of gas current. Although there is an increase of electron temperature with gas current, it is not large. If the measurement of electron temperature in Fig.6 for 10.5 kV and 200 kA is extended to the peak value of gas current at 300 kA by using the rough estimate of the temperature-current gradient (0.012 eV/kA), an increase in electron temperature of about 1.2 eV is obtained. This increase is consistent with the data on electron temperature versus gas current in Fig.6.

The dependence of the electron temperature on the deuterium gas pressure for a constant value of capacitor bank voltage (10.5 kV) and constant θ (2.0) is given in Fig.7. The added nitrogen concentration also was kept constant at 5×10^{-6} Torr for these data. This is the same as the nitrogen concentration used for the data presented in Figs. 4–6 (1/2 mTorr D_2 + 1% N_2). The electron temperature decreases rapidly with increasing deuterium pressure above about 0.5 mTorr. The time of appearance of the transients of the NV ion occurs before the peak value of gas current for a pressure of 0.5 mTorr (Fig.4), and shifts toward peak gas current with increasing pressure. At a deuterium pressure of 2 mTorr, the emission lines of NV occur essentially at the peak value of gas current.

4.2 Validity of Measurements

Criteria for the validity of this method of measuring electron temperature were given in section 2. These are stated by the inequalities (3) and (4) together with the assumption of a Maxwellian velocity distribution.

Taking 10 eV as a lower limit of the range kT_e covered by the measurements and since $\chi_i \sim 100$ eV for NV, inequality (3) reduces to $n_e \leqslant 10^{16}$ cm^{-3}. Since the maximum value of n_e is about 2×10^{14} cm^{-3}, this criterion is easily met. Thus the assumption of coronal type excitation processes, as represented by equation (1), is valid. A partial

experimental check of this was possible since the two most important secondary processes populating level $2p^2P^o_{3/2}$ could be measured directly. These are radiative cascade transitions from the $3d^2D$ and $3s^2S$ levels. The intensities of the corresponding lines (at 247.6 Å and 263.3 Å respectively in NV) were measured and found to contribute less than 2 per cent of the population of the $2p^2P^o_{3/2}$ level.

The initial nitrogen concentration for all data presented above is 3.6×10^{11} cm^{-3}. If it is assumed that all atoms are in the ground state of the NV ion, a safe upper limit for the number of NV ground state ions in the line of sight Dn_1 is 3.6×10^{13} cm^{-2}. Criterion (4) requires that this be less than 4×10^{13} cm^{-2}. This was calculated by using the measurements of ion energy in ZETA made by Jones and Wilson (1961). Since the calculated value of Dn_1 is an upper limit, this inequality can be taken as satisfied and not marginal, particularly when an application of the work of Hearn (1963) shows that the criterion is relaxed by a factor of ten in the coronal domain. This criterion was also checked experimentally by measuring the intensity ratio of the components in the resonance doublet I(1238.8 Å)/I(1242.8 Å). This ratio was observed to be 2.0 (± 10%) which agrees with the theoretical ratio (2.0) for conditions of optical thinness.

The electron-electron relaxation time (Spitzer 1956) varies between 10^{-7} and 10^{-8} sec for the range of conditions studied here. This time is short enough to maintain a Maxwellian distribution of electron velocities, although departures may be expected for electron densities below 10^{13} cm^{-3} (McWhirter 1959); the present observations were made at electron densities between about 4×10^{13} cm^{-3} and 2×10^{14} cm^{-3}. However, non-thermal electrons of mean energy about 8 kV have been observed in these conditions when the electron density is low. This occurs both at the beginning of the pulse when the ionization is low and at the end of the pulse when the plasma has pumped-out (Gibson and Mason 1962). These times are well removed from the times of observation of the NV lines discussed here. In any case, a non-Maxwellian tail at 8 kV populated by one per cent of the electrons (an upper limit) would alter the observed intensity ratio of the NV lines by only one per cent.

4.3 Accuracy of Measurement

Errors of measurement arise from three sources: (i) the accidental errors involved in the measurement of the ratio of signals of the two lines; (ii) errors in the photometric calibration, and (iii) errors in the cross section for electron impact excitation. The first is due mainly to variations in the signal from discharge to discharge and is estimated as ± 10% in the final observed ratio, based on a mean of 40 observations on each line. The corresponding error in kT_e (for a value near 20 eV) is ± 0.8 eV.

The method of obtaining a relative photometric calibration at 1238.8 Å and 209.3 Å, the wavelengths of the NV lines, was described in section 3.2 and the error estimated at ± 25%. The corresponding error in kT_e (for a value near 20 eV) is ± 2.5 eV.

It is difficult to make an assessment of the uncertainties in the electron impact cross sections used since no experimental values for ions are available. However, if we use the excitation function derived by Woolley and Stibbs (1953) using essentially a classical cross section, the calculated intensity ratio for kT_e = 20 eV would be greater by about a factor of two than that derived for the Seaton cross section. On the other hand, if the latter cross section were applied to an atom, with the relevant value of $\bar{g}\ (\chi/kT_e)$, the discrepancy in the ratio would be reduced to about 30%, and it seems reasonable to assume that the difference is largely due to the allowance, made by Seaton, of the coulomb field of the ion. Considering the very different theoretical approaches in deriving the two cross section, it is reasonable to take a factor of two as an upper limit in error for the ratio due to cross section uncertainties. The corresponding upper limit in the error of kT_e (near 20 eV) is ± 5 eV.

Summarising, the measured values of electron temperature given in figures 5, 6 and 7 and subject to a random error of ± 4%, but with a possible system error, due to uncertainties in calibration and cross section, estimated as ± 30%.

5. DISCUSSION

Estimates of the electron temperature in ZETA have been made previously by a variety of methods. Estimates based on the temporal variation of line intensities of impurity ions (Burton and Wilson, 1961) and an electrostatic probe analyser placed near the torus wall (Gibson and Mason, 1962) are summarised by Burton et al. (1961). Earlier estimates, based on measurements of microwave noise and the intensity of the CV $2^3S - 2^3P^o$ line at λ 2271 were made by Butt et al. (1958). These various estimates gave a range of values of kT_e between about 15 and 35 eV for discharge conditions similar to those for which the present method gives 20–26 eV.

One of the main restrictions in the application of the present method is the limitation imposed by the time of appearance of the NV emission lines. Additional measurements at different times during the discharge are possible by using other species of Li-like ions, and this is dependent on an extension in the wavelength range of the photometric calibration. This is a difficult problem, particularly for the shorter wavelengths. With such an extension, this method is potentially powerful in its range of applicability. Apart

from errors in calibration, the ultimate accuracy of the method in determining electron temperatures will depend upon the accuracy of the excitation rate coefficient.

6. CONCLUSIONS

(a) A method of measuring the electron temperature in a high temperature and optically thin plasma is presented, based on the measurement of the spectral line intensity ratio of the 2s-2p and 2s-3p transitions from the same species of Li-like ion. The theoretical dependence of the intensity ratio on electron temperature is calculated for several ions of the sequence between CIV and SiXII and given in Fig.2.

(b) The application of this method is dependent on a photometric calibration in the extreme ultra violet and soft X-ray regions of the spectrum. This was accomplished by combining the calibration of a GRD grazing-incidence rocket monochromator (reference tungsten cathode) with the branching ratio method of calibration using emission lines from the HeII ion.

(c) The range in calibration limited the use of the method to the NV ion. Using this ion, the electron temperature in ZETA was measured over a range of discharge conditions and the results are given in Figs. 5-7. The earlier rough estimates in ZETA show an order of magnitude agreement with these results.

(d) The method is potentially powerful and accurate. Its range of applicability can be extended considerably by using other species of Li-like ions. This, however, is dependent on an extension in wavelength in the photometric calibration. Apart from errors in calibration, improvements in accuracy will depend on improvements in the determination of the cross sections for excitation by electron impact.

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TABLE I

Atomic Parameters for Lithium-like Ions

ion	trans-ition	σ^2	J	λ Å	f	A sec^{-1}	
CIV	2s-2p	0.48	1/2-3/2 1/2-1/2	1548.20 1550.77	0.19 0.09	2.6×10^8 2.6×10^8	(a), (d)
	2s-3p	0.07	1/2-3/2 1/2-1/2	312.42 312.45	0.14 0.07	46 46	(a), (e)
NV	2s-2p	0.31	1/2-3/2 1/2-1/2	1238.80 1242.78	0.16 0.08	4.0 4.0	(a), (d)
	2s-3p	0.054	1/2-3/2 1/2-1/2	209.27 209.30	0.16 0.08	120 120	(a), (e)
OVI	2s-2p	0.23	1/2-3/2 1/2-1/2	1031.91 1037.61	0.14 0.07	4.2 4.2	(a), (d)
	2s-3p	0.04	1/2-3/2 1/2-1/2	150.09 150.12	0.16 0.08	240 240	(a), (d)
NeVIII	2s-2p	0.129	1/2-3/2 1/2-1/2	770.42 780.34	0.10 0.05	5.6 5.5	(b), (e)
	2s-3p	0.029	1/2-3/2 1/2-1/2	88.09 88.12	0.20 0.10	860 860	(c), (e)
MgX	2s-2p	0.08	1/2-3/2 1/2-1/2	609.85 625.28	0.09 0.03	7.6 7.2	(a), (d)
	2s-3p	0.02	1/2-3/2 1/2-1/2	57.86 57.92	0.23 0.10	2200 2200	(a), (d)
SiXII	2s-2p	0.06	1/2-3/2 1/2-1/2	499.28 521.11	0.08 0.04	9.4 8.6	(a), (e)
	2s-3p	0.015	1/2-3/2 1/2-1/2	40.9 40.9	0.22 0.11	4400 4400	(c), (e)

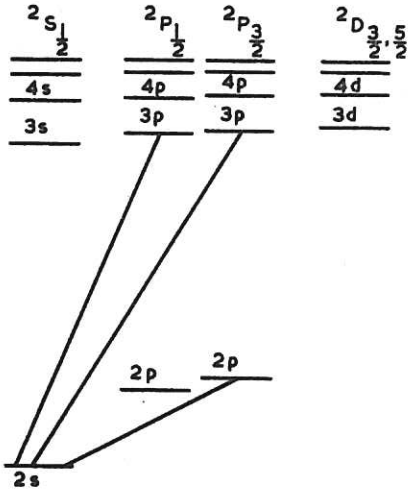
(a) Wavelengths from Moore (1949).

(b) Wavelengths from Fawcett, Jones and Wilson (1961).

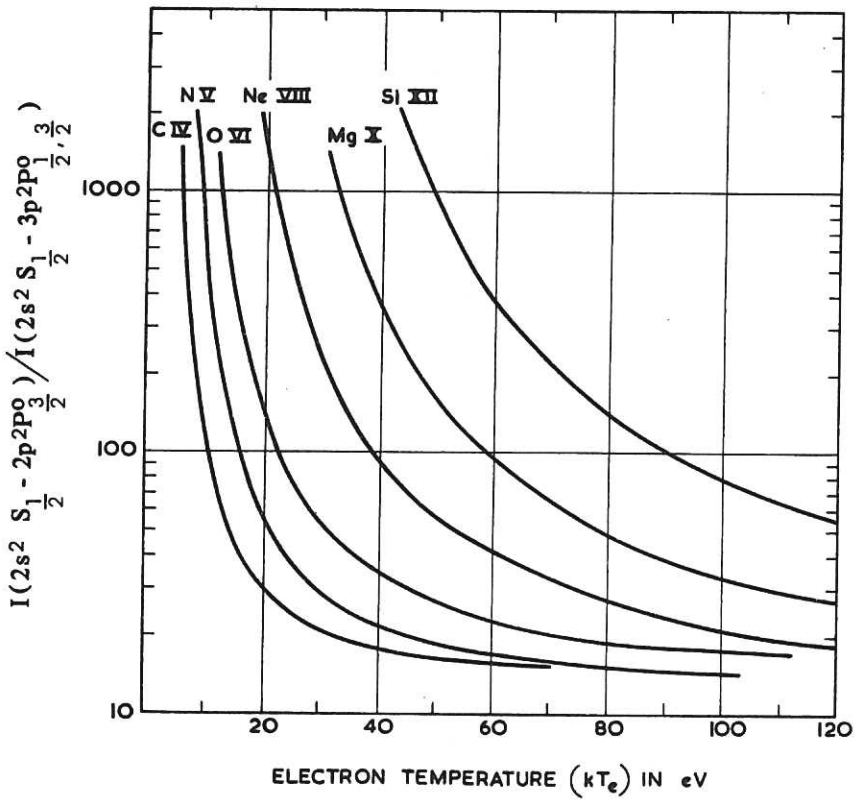
(c) Wavelengths from an iso-electronic extrapolation.

(d) σ^2, f, and A from tables by Allen (1955).

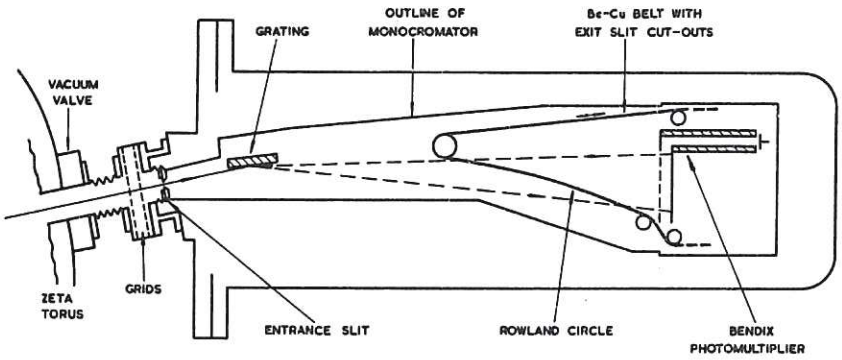
(e) σ^2, f, and A calculated here using approximation of Bates and Damgaard (1942).



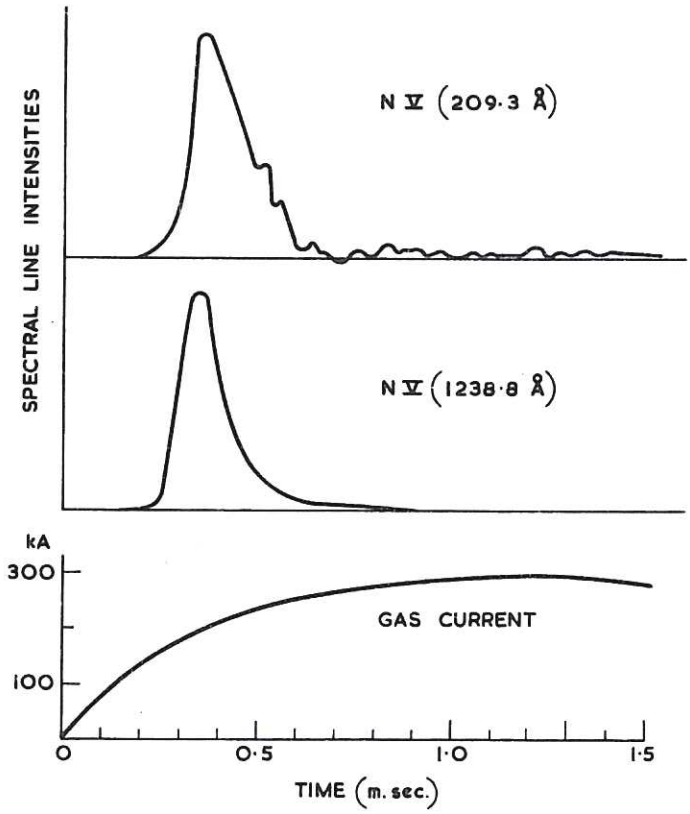
CLM - P 30 Fig. 1 Illustration of the Li-like ion energy level scheme.



CLM - P 30 Fig. 2 The theoretical spectral line intensity ratio of the transitions $2s^2S_{1/2} - 2p^2P^o_{3/2}$ and $2s^2S_{1/2} - 3p^2P^o_{1/2,3/2}$ versus kT_e for several ions of the Li-like isoelectronic sequence.

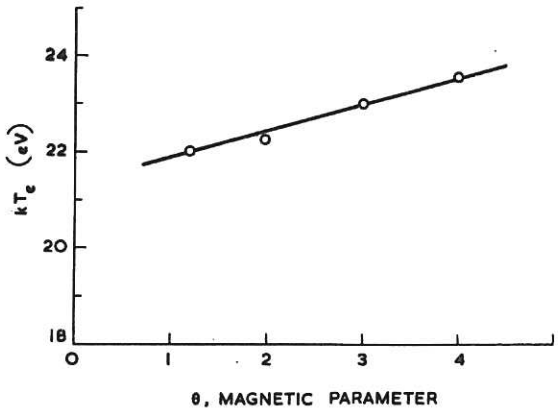


CLM - P 30 Fig. 3 Schematic illustration of the grazing-incidence rocket monochromator and its coupling to ZETA.



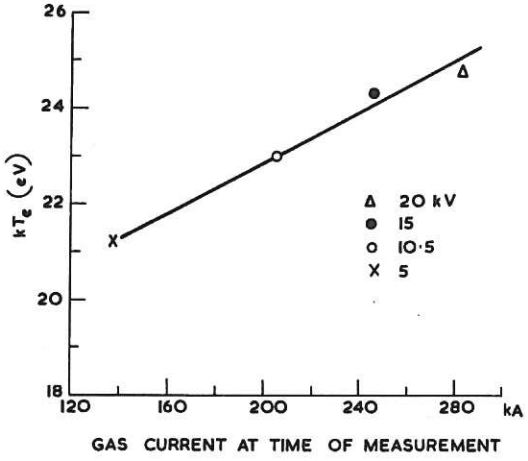
CLM - P 30 Fig. 4

Typical intensity-time profiles of the NV ion emission lines $2s^2S_{1/2} - 2p^2P^o_{3/2}$ (1238.8 Å) and $2s^2S_{1/2} - 3p^2P^o_{1/2,3/2}$ (209.3 Å). Part of the gas current waveform is also shown. (P = 1/2 mTorr D_2 + 1% N_2, V_c = 10.5 kV, B_z = 600 gauss).



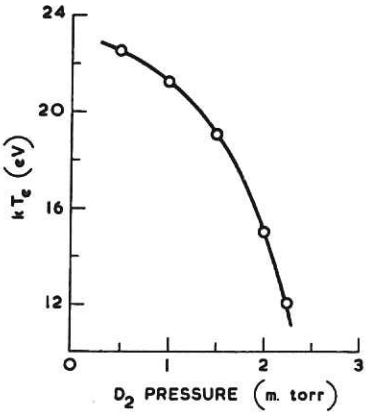
CLM - P 30 Fig. 5

Dependence of electron temperature in ZETA on magnetic parameter θ. (P = 1/2 mTorr D_2 + 1% N_2, V_c = 10.5 kV).



CLM - P 30 Fig. 6

Measurements of electron temperature in ZETA for four values of capacitor bank voltage. The abscissa gives the value of gas current at the time of measurement of electron temperature. (P = 1/2 mTorr D_2 + 1% N_2, θ = 2.0).



CLM - P 30 Fig. 7

The dependence of electron temperature in ZETA on deuterium pressure. The nitrogen (N_2) impurity concentration was maintained constant at 5×10^{-6} Torr. (V_c = 10.5 kV, θ = 2.0).