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CORONA APPROXIMATION OF THE PLASMA[1])

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Difficulties in the determination of basic parameters of the plasma can be solved in several cases by using the corona approximation of plasma. Under certain conditions discussed later one can obtain electron temperature and density in non-equilibrium plasma.

For temperature and density measurements we use in general the ratio of relative intensities of two spectral lines. If we need both parameters, we must use two independent ratios, i.e. we must use three spectral lines. For temperature measurements we use two lines of the same ionization stage and for density measurements we use two lines of subsequent ionization stages.

МОДЕЛЬ ПЛАЗМЫ В ПРИБЛИЖЕНИИ КОРОННОГО РАЗРЯДА

Трудности с определением основных параметров плазмы в некоторых случаях можно решить при помощи использования модели плазмы в приближении коронного разряда. При некоторых условиях, которые подробно обсуждаются в статье, можно получить температуру и плотность электронов в неравновесной плазме. Для измерений температуры и плотности в общем использовано отношение относительных интенсивностей двух спектральных линий. В случае необходимости одновременного определения обоих параметров необходимо использовать два независимых отношения, т.е. необходимо использовать три спектральных линии. Для измерений температуры были использованы две спектральных линии одной и той же ступени ионизации и для измерения плотности были использованы две спектральных линии двух последовательных ступеней ионизации.

I. THEORY

The basic presumption of the corona approximation is that the dominant process in the plasma is excitation of the neutral atoms by the electron impact. All other processes (ie. ionization, cascade processes etc.) are negligible. We must further presuppose that excitation by the electron impact is not balanced by a correspond-

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ing collisional process (i.e. by superelastic collision), but is balanced by radiative deexcitation. And finally we must consider the plasma to be optically by thin.

From all these presumptions the limitations of our approximation follow. After Drawin [1] electron density is limited by the value $10^{18}\,\mathrm{m}^{-3}$ and neutral atom density is limited by the value $10^{18}\,\mathrm{m}^{-3}$. These restrictions follow from the computer model of the plasma.

After Sovie [2] the intensity of the spectral line I_{jk} corresponding to the $j \to k$ transition is given by

$$I_{jk} = N_0 N_e \langle Q_{jk}(v)\, v \rangle , \tag{1}$$

where N_0, N_e, v and $Q_{jk}(v)$ are neutral atom density, electron density, electron velocity and excitation function of the $j \to k$ transition, respectively. The brackets $\langle\ \rangle$ indicate a value averaged over the distribution function of the electrons.

For the intensity of the ionic spectral line I^+_{jk} we obtain in analogy with the previous case

$$I^+_{jk} = N_+ N_0 \langle Q^+_{jk}(v)\, v \rangle , \tag{2}$$

where N_+ is ion density and all other symbols are the same as above.

From the ratio of intensities of two spectral lines of the same ionization stage we can obtain the electron temperature. This ratio is

$$\frac{I_{jk}}{I_{lm}} = \frac{\langle Q_{jk}(v)\, v \rangle}{\langle Q_{lm}(v)\, v \rangle} . \tag{3}$$

This formula is valid both in the case of two neutral lines and in the case of two ionic lines. The right-hand side (RHS) of equation (3) is the function $f(T_e)$ of electron temperature T_e. If we determine numerically the dependence $f(T_e)$ versus T_e and if we measure the ratio of intensities on the left-hand side (LHS), we can determine the electron temperature T_e.

The ratio of intensities of two spectral lines of the subsequent stage of ionization can be used for the electron density determination. In analogy with equation (3) we obtain

$$\frac{I_{jk}}{I^+_{lm}} = \frac{N_0}{N_+} \frac{\langle Q_{jk}(v)\, v \rangle}{\langle Q^+_{lm}(v)\, v \rangle} . \tag{4}$$

On principle we are able to determine the function

$$F(T_e) = \frac{\langle Q_{jk}(v)\, v \rangle}{\langle Q^+_{lm}(v)\, v \rangle} \tag{5}$$

on the RHS of equation (4) numerically. The ratio of intensities on the LHS of equation (4) can be measured so that it is possible to determine the ratio N_0/N_+ in equation (4) if we know the electron temperature T_e. This value though can be

determined by the preceding method. For the N_+ determination is sufficient if the pressure of the gas in the discharge tube is known. Then from the equation

$$p = N_0 k T , \tag{6}$$

where p, k and T are the pressure, Boltzmann's constant and absolute temperature, we can obtain N_0 and from the ratio N_0/N_+ the N_+. As in the plasma relation of quasineutrality

$$N_+ = N_e \tag{7}$$

holds, the value of N_e is also given.

The main role in the functions $f(T_e)$ and $F(T_e)$ play the values of $\langle Q_{jk}(v)\, v \rangle$ which in accordance with Latimer et al. [3] we call optical cross sections.

II. DETERMINATION OF THE OPTICAL CROSS SECTIONS

The value of the optical cross section is the average value taken over the distribution of electrons. Because the values of $Q_{jk}(v)$ are known numerically only, we must integrate numerically on the computer.

For the distributions of electrons we took the Maxwellian

$$g(E) = A_1 \sqrt{E} \exp(-E/T) \tag{8}$$

and Druyvestein's

$$g(E) = A_2 \sqrt{E} \exp(-0.5(E/T)^2) \tag{9}$$

where E, A and T are energy in eV, normalization constant and absolute temperature in eV, respectively. From these distributions there follow the equations for the optical cross sections; for the Maxwellian case

$$\langle Q_{jk}(v)\, v \rangle = 6.692 \times 10^7 \, (1/T)^{3/2} \int_{E_{min}}^{E_{max}} Q_{jk} E \exp(-E/T)\, \mathrm{d}E \tag{10}$$

and the Druyvestein case

$$\langle Q_{jk}(v)\, v \rangle = 4.070 \times 10^7 \, (1/T)^{3/2} \int_{E_{min}}^{E_{max}} Q_{jk} E \exp(-0.5(E/T)^2\, \mathrm{d}E \tag{11}$$

where E_{min} is threshold energy and E_{max} is maximal energy taken in accordance with [3] as $E_{max} = 10\,\mathrm{T}$.

The integration formula used was the Simpson formula and all evaluations were carried out on an Odra 1204 computer.

III. RESULTS FOR HELIUM

In this paper we considered S levels only, because only these levels have Q_{jk} values independent of the pressure of gas. We used the method of Cunningham [4]. We took into account six transitions of neutral helium

$3^1S \rightarrow 2^1P$ 721.8 nm $3^3S \rightarrow 2^3P$ 706.5 nm
$4^1S \rightarrow 2^1P$ 504.8 nm $4^3S \rightarrow 2^3P$ 471.3 nm
$5^1S \rightarrow 2^1P$ 443.8 nm $5^3S \rightarrow 2^3P$ 412.0 nm

and four transitions of the helium ion

$3 \rightarrow 4$ 468.6 nm $3 \rightarrow 5$ 320.3 nm $3 \rightarrow 6$ 273.3 nm $3 \rightarrow 7$ 251.1 nm.

The values of excitation functions were taken from R. M. St. John [5, 6], M. Moussa [7] and P. Laborie, M. Rocard [8].

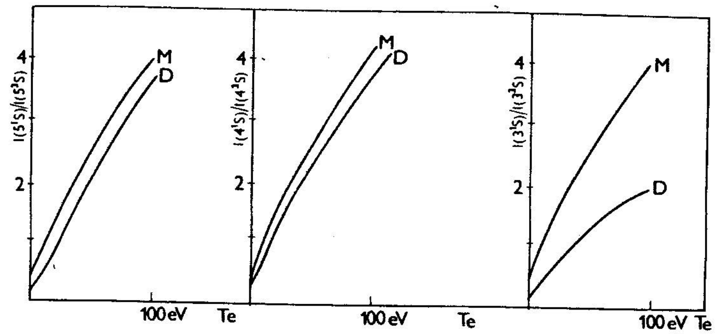
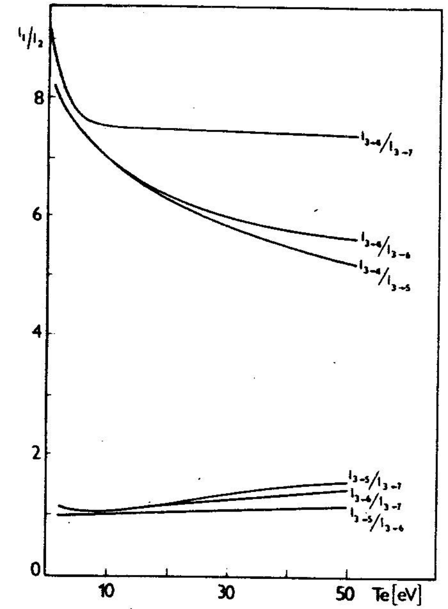


Fig. 1. Ratio of intensities of neutral spectral lines of helium. M — Maxwell distribution, D — Druyvestein distribution.

Results are shown on graphs. Fig. 1 shows the dependence $f(T_e) \sim T_e$ for the case of neutral helium and both distributions of electrons. It is evident that the function $f(T_e)$ is monotonously increasing with T_e. Fig. 2 shows the dependence $f(T_e)$ for ionic helium lines in the case of the Maxwellian distribution. It is evident that for diagnostic purposes the best is a ratio of intensities of lines 468.6 nm and 320.3 nm. All the other ratios are partly constant with T_e in the whole region of T_e, partly constant in some part of the region of T_e. Only the ratios of lines 468.6 nm, 320.3 nm and 468.6 nm, 273.3 nm are monotonously decreasing with T_e; but the first two lines are evidently better than the other two lines. Fig. 3 shows the dependence $f(T_e)$ for ionic helium lines in the case of the Druyvestein distribution. The conclusions are the same as in the previous case.

Fig. 4 is an example of a nomogram for density determination. Electron density can be determined in the following way: first we have to determine the electron

Fig. 2. Ratio of intensities of ionic spectral lines of helium for the case of Maxwell distribution.



temperature. We plot this value on a vertical axis in the lower part of the nomogram, which contains the dependence $F(T_e) \sim T_e$. From this dependence we determine the corresponding point on the horizontal axis. On the upper part of the vertical axis we plot the value of I_{jk}/I^+_{lm}. Through both points we put lines parallel to the corresponding axis. The point of crossing determines then the value of $\alpha = N_+/N_0$. Knowing the pressure p in the discharge tube we can obtain N_e from α as described above.

IV. EXPERIMENT

Theoretical conclusions of the preceding parts were proved experimentally on the glow discharge in helium. We proved the temperature determination only, since in the glow discharge it was impossible to excite any ionic line.

We used two values of the discharge current; 10 mA and 15 mA. In both cases the electron temperature was determined on the basis of the above theory. In the case of the discharge current 10 mA we could determine the electron temperature from the ratio of the intensities of lines 504.8 nm and 471.3 nm. The temperature value was 20300 K. In the case of the discharge current 15 mA we could determine the electron temperature from the ratios of the intensities of lines 504.8 nm and 443.8 nm, 412.0 nm. From the first ratio the electron temperature obtained was 45800 K and from the second 48600 K.

As a testing method the double probe method was used. In the case of the discharge current 10 mA we obtained the value of the electron temperature 20300 K and in the case of the discharge current 15 mA we obtained the value of electron temperature 44500 K.

From the above experimental data it follows that the values of T_e obtained by both methods are practically equal and the accuracy of measurement is better than 10 %. Because of this fact we are able to compare our results with those of Drawin [1]. Our results show that the corona approximation can be used at neutral atom densities higher than 10^{18} m^{-3}. Our value of neutral atom density was about 10^{23} m^{-3}.

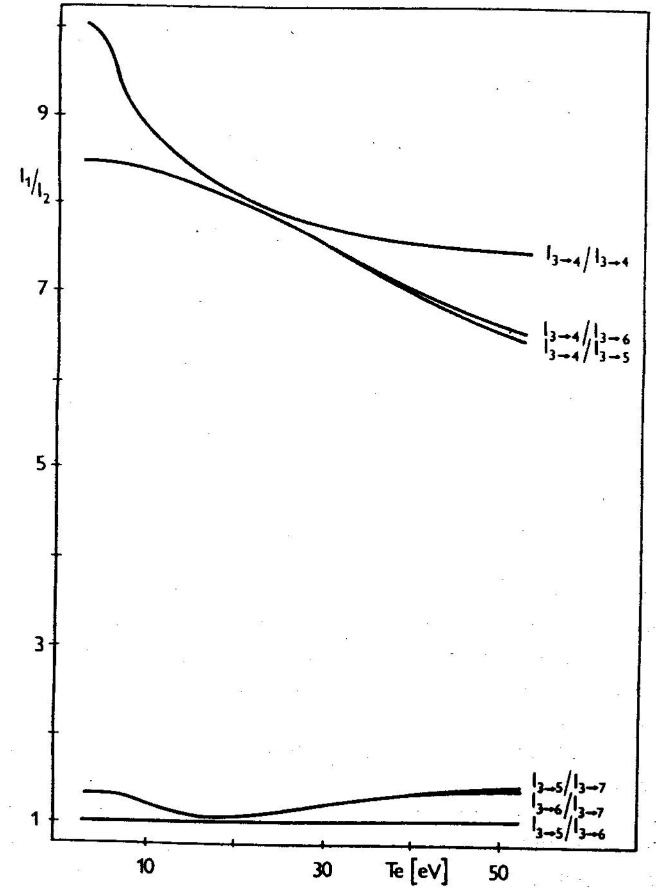


Fig. 3. Ratio of intensities of ionic spectral lines of helium for the case of Druyvestein distribution.

Hence we can conclude that for helium glow discharges it is possible to use the corona approximation for the temperature determination. It is possible to use this approximation in a nonequilibrium discharge under similar conditions. The value of 10^{18} m^{-3} is limiting for the electron density only. As the principle of density determination is similar to that of temperature determination, we can expect that also density determination will be possible in the range of the corona approximation.

But it is necessary to observe that for an exact diagnostic it is necessary to use tables of optical cross sections, to be published later in a special report.

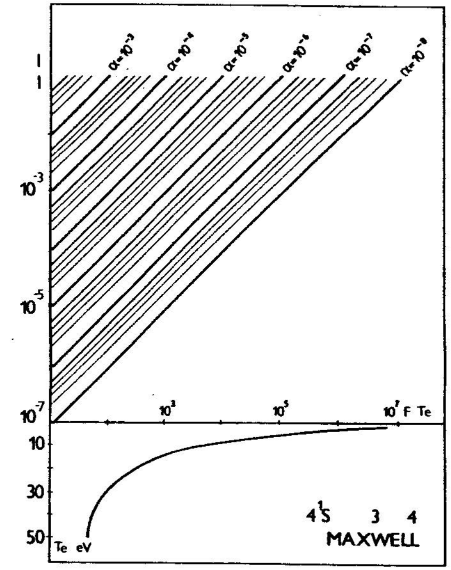


Fig. 4. Nomogram for electron density determination.

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