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CONTINUOUS EMISSION, LOWERING OF THE IONIZATION POTENTIAL AND TOTAL EXCITATION CROSS-SECTIONS OF AN ATMOSPHERIC THERMAL PLASMA

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Introduction. A careful study of the relation between the electron density, $n_e$, and the electron temperature, $T_e$, in an atmospheric arc plasma, shows an approach to local thermodynamic equilibrium (LTE) at large values of $n_e$ [1]. Our measurements can be interpreted in terms of a Partial LTE (PLTE) model, in which the ground state is overpopulated with respect to the other excited states. This overpopulation is shown to be caused by radiative recombination in ref. [1].

The relative overpopulation of the ground state as a function of $T_e$, is fairly sensitive to small variations in, both, the transition probability, $A$, and the value for the lowering of the ionisation potential, $\Delta \chi_0$; when an accurate value of $A$ is available, an estimate of $\Delta \chi_0$ can be made. The total cross-section for excitation from the neutral ground state was derived from the measured degree of overpopulation. In addition we calculated the emissivity of the free-bound UV recombination radiation, which proves to be quite large in the 70-80 nm spectral range. Finally, we give some results for the continuum radiation and for the Stark parameters at $\lambda = 700$ nm.

Experimental method and data handling. The experimental method has been described in [1]. It is based on the assumption of PLTE. The source function, $S$, is then given by

$$S = \epsilon(\lambda) = \frac{2hc^2}{\lambda^5} \left[ \exp\left(\frac{hc}{\lambda k T_e}\right) - 1 \right]^{-1}.$$ 

The source function has been determined for several transitions in the Ar neutral spectrum. To this end we measured emission and absorption ($\lambda$-)profiles of selected lines (with appropriate optical thickness; $1 < \kappa(\lambda) k < 3$), at 300-1000 $\lambda$-positions over the wavelength range of the line and its adjacent continuum. The line source function proved to be constant over the line profile, and close to the continuum source function.

The experimental profiles were then fitted with theoretical Voigt profiles, for $\epsilon(\lambda)$ and $\kappa(\lambda)$, by a least squares minimisation procedure, with parameters: the source function, the optical thickness at the line center, the continuum absorption as a function of wavelength, the position of the line center, the lorentzian width of the line, and a factor accounting for the total transmissivity of the optical system. The gaussian component of the profiles was set equal to the Doppler width at $T_e$.

Each theoretical profile was then convolved with the measured apparatus profile of the monochromator used, and compared with the measured profile. Iteratively the best fit was obtained. In this way $T_e$ was determined using all the available information. In addition, line broadening parameters and continuum emissivities were obtained. $n_e$ was calculated from the emission coefficient using Saha's equation. The neutral density, $n_0$, followed from Dalton's law ($p = nkT$). This value of $n_e$ was then compared with the value, $n_{o,s}$, obtained from LTE, in order to calculate the overpopulation of $n_0$.

Results. The measurements, mainly on the 696.5 nm line, were carried out in an atmospheric, water cooled arc plasma. The channel diameter is $5 \times 10^{-3}$ m and the plasma length is $9.7 \times 10^{-2}$ m. The arc current was varied from 40 A to 250 A.

1. Influence of $\Delta \chi_0$ and $A$. Figure 1 is a plot of the overpopulation of the ground level, expressed in $b = n_0/n_{o,s}$, which shows the expected asymptotic behaviour, approaching 0 at large values of $T_e$. In the calculation of $b(T_e)$ we used $A = 67 \times 10^5$ and $\Delta \chi_0$ from Ecker and Kroll's formula (cf. [2]).

The function $b(T_e)$ is very sensitive to variations $\Delta A$ in $A$ and $\delta(\Delta \chi_0)$ in $\Delta \chi_0$:

$$\delta b = \frac{n_e}{n_{o,s}} \delta(\Delta \chi_0) + \frac{\delta A}{A}.$$ 

In particular at high temperatures, when $n_e/n_{o,s}$ becomes large and the asymptotic behaviour of $b(T_e)$ is known, minimization of $\delta b$ can provide additional...
Fig. 1 Overpopulation factor \( b = n_0 / n_e \) as a function of \( T_e \) for Ar at 1 atm. curve (1) with \( \Delta x_0 \) from Ecker-Kroll curve (2) with \( \Delta x_0 \) from Unsold, Ecker-Weizel, Brunner

information on \( A \) and \( \Delta x_0 \). Assuming \( A \) to be more accurately known than \( \Delta x_0 \) we investigated the effect of different assumptions in the calculation of \( \Delta x_0 \) on \( b(T_e) \). The result is given in fig. 1, in which curve 2 is the \( b(T_e) \) relation obtained with the same value of \( A \) as in curve 1, but a different value of \( \Delta x_0 \) : a mean value from the calculations of Unsold, Ecker-Weizel and Brunner (e.g. [2]). As can be seen curve 2 does not show the expected asymptotic behaviour, indicating that Ecker and Kroll's formula, in which the Debye length is used instead of the interparticle distance, is more satisfactory.

2. Total excitation cross-section. Assuming that radiative recombination to the ground level is the dominant mechanism causing the overpopulation in our PLTE model, we find, using the principle of detailed balancing:

\[
b = \frac{n_0}{n_e} \frac{\gamma_{3p}^{(2)}(T_e)}{\gamma_{3p}^{(1)}(T_e)}.
\]

\( \gamma_{3p}^{(2)}(T_e) \), the radiative recombination coefficient, can easily be found from detailed balancing, using the published values for the photo-ionisation cross-section (cf. [3]). It is more difficult to obtain accurate values for \( \gamma_{3p}(T_e) = \sigma < e^-< e^+ > + < e^-< e^- > \) the total excitation and ionisation cross-section from the ground level. Especially in the temperature range of interest (1-1.5 eV) the excitation cross-sections \( \sigma(v_e) \) are not accurately known and depend much on the threshold behaviour, which in its turn is also not accurately known. With theoretical values for \( \gamma_{3p}^{(2)}(T_e) \), [3], we have determined \( \gamma_{3p}(T_e) \) from the measured values of \( b \) and \( n_e \). The result is given in fig. 2 (points). The qualitative dependence of \( \gamma_{3p}(T_e) \) is less steep than indicated in the literature.

Fig. 2 Total excitation and ionisation cross-section \( \gamma_{3p} \), as function of \( T_e \), for Ar at 1 atm. Also shown is the radiative recombination coeff. \( \beta_{3p}^{(2)} \).

\( \gamma_{3p}^{(lit)} \): literature values for \( \gamma_{3p} \)

\( \gamma_{3p}^{exp} \): measured values for \( \gamma_{3p} \)

3. Continuum emission and Stark parameter. Using the theoretical values for \( \beta_{3p}^{(2)} \), we calculated the total power of the continuum free-bound radiation, which amounts to about 1 kW per cm arc length, for \( \lambda = 72 \) to 78 nm. This makes similar arcs very attractive as "light" sources. From our fitting procedure we also obtained the Birnbaum factor, \( \varepsilon_{fb} \) (at \( \lambda = 700 \) nm) and the Stark broadening parameter, \( \alpha \). The results are summarized in table 1. The continuum absorption and the \( \varepsilon_{fb} \) values agree with Schlüter's values [4,5].

The mean value for \( \alpha \), \( \alpha = 7.4 \times 10^{-24} \text{ cm}^3 \) differs by almost 40% from Griem's value, \( \alpha = 12 \times 10^{-24} \text{ cm}^3 \) [6].

Table 1.

<table>
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<th>I [A]</th>
<th>( T_e ) [10^3 K]</th>
<th>( n_e ) [10^19 m^-3]</th>
<th>( K_{3p} ) [m^-1]</th>
<th>( K_{cont} ) [m^-1]</th>
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References.