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CONTRIBUTIONS FROM ION-ATOM CHARGE EXCHANGE COLLISIONS TO THE CVI LYMAN
INTENSITIES IN THE JET TOKAMAK

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RESUMÉ Dans les plasmas en deutérium du JET avec une température électronique de quelques keV les raies émises par CVI sont causées par des processus collisionnels près du bord, en absence de chauffage par injection de neutres. Le décrement de la série de Lyman est modifié, ceci étant relié à l'intensité de la raie D_α et, par conséquent, au flux périphérique d'atomes neutres D^0 .

L'intensité du spectre de la série de Lyman est interprétée en terme de collisions d'échange de charge à faible énergie entre les atomes D^0 thermiques et les ions C^{6+} et en terme de collisions électroniques des ions C^{5+} dans leur état fondamental. L'émission intégrée le long d'un diamètre est interprétée en utilisant un code de simulation d'impuretés.

Pour avoir un bon accord avec l'expérience aux grandes valeurs du flux d'atomes D^0 il faut considérer l'échange de charge avec les atomes D^0 dans leur état fondamental ainsi que dans leurs états excités, les sections efficaces pour ce dernier cas sont estimées en utilisant le modèle de Landau-Zener. Les comparaisons relatives des intensités expérimentales et des intensités calculées permettent d'évaluer des facteurs correctifs aux taux effectifs d'excitation par échange de charge.

Ces observations constituent une méthode potentielle d'évaluation de la densité locale de D^0 à la périphérie de plasmas chauds à fort recyclage de D^0 , limitée toutefois par les incertitudes actuelles sur les sections efficaces d'échange de charge à faible énergie.

ABSTRACT In a multi-keV temperature deuterium plasma such as JET, CVI emission arises from collision processes which, in the absence of neutral deuterium beam heating, occur near the plasma boundary. Distortions to the CVI Lyman decrement, such as the Ly $\beta/\gamma/\delta$ ratio and enhancement of the high quantum states ($n \geq 12$) are observed. These are correlated to the D_α intensity and consequently to the influx of D^0 atoms at the plasma boundary.

The intensities of the Lyman spectra are interpreted in terms of low energy electron transfer from thermal D^0 atoms to C^{6+} ions as well as electronic excitation of C^{5+} ions in their ground state. The line-of-sight emission is modelled using an impurity ion transport code with input data on the electron and D^0 profiles.

Electron transfer from excited states of D^0 (up to the thermal limit) as well as the ground state have to be included to give satisfactory agreement with the CVI Lyman spectra when the D^0 influx is high. The cross-sections for charge-transfer from excited states have been estimated using a simple Landau-Zener model. Comparison of the relative intensities of the CVI Lyman series Ly $\beta/\gamma/\delta$ etc with the model calculations allows plausible corrections to be made to the effective charge transfer cross-section as a function of principle quantum number.

The observations offer a potential method of measuring local D^0 concentrations near the boundary of high temperature, high D^0 recycling plasmas, but limited at present by the uncertainties of low energy charge transfer cross-sections.

1 INTRODUCTION The importance of charge transfer (CX) collisions between atoms and ions in keV and multi-keV temperature plasmas of interest in controlled fusion research has been appreciated for a decade or so [1]. Not only can charge transfer alter the local ionisation balance [2] and the location within the plasma of the radiation shell associated with each ion species; but the radiation signature of the ions can also be modified. This is especially true for bare nuclei such as D^+ , He^{2+} , C^{6+} , O^{8+} etc. which ordinarily radiate only a weak continuum from the plasma volume. Charge transfer, being state selective [3] [4] [5], endows the recombined ion with a very specific line emission signature. The most intense charge exchange lines result from $\Delta n=1$ transitions which represent the most probable decay routes to ground from the dominant quantum levels selected by the charge transfer process.

The CX spectral signature depends on the atomic structure of the recombining ion and the relative velocity of the colliding particles. In fusion plasmas equivalent energies, E_0 , of the impacting H^0 , D^0 atoms range from several keV/AMU characteristic of beam atom energies, though $E_0 \sim 1 \text{ keV/AMU}$ for the secondary 'halo' atomic products produced by beam-ion collisions, to low energy collisions $E_0 < 1 \text{ keV/AMU}$ involving 'background' atoms diffusing into the plasma boundary. In practice, the intensities of the $\Delta n=1$ lines involving the dominant excited states eg. $n \sim 4$ for $[C^{5+}]^*$, appear in the VUV region and these intensities are in satisfactory agreement with the various theoretical estimates for the charge transfer cross sections [1].

In beam-plasma interaction experiments, transitions involving much higher (Rydberg-like) levels, $n > 2n$ for example, can also appear as part of the CX-signature [6] despite the considerably lower cross-section for selecting these high levels. The explanation for these $\Delta n=1$ lines, which typically appear in the visible or near visible region of the spectrum, is more complicated however, due to other possible excitation processes [7] and the possibility of line blending with emissions from other ions with the same effective charge [6] [7]. Magnetic and electric fields imposed by the plasma environment itself has the effect of mixing the (n, j, l) states [8]. The charge exchange signature can, through mixing of high l -sub levels with the s, p, d orbital quantum states, appear not only in the visible $\Delta n=1$ transitions but also in the resonance lines, such as the Lyman series of CVI.

Another complication to the CX population of Rydberg levels is the electron transfer from excited states of the donor atom. The charge transfer cross-section scales approximately as the n_0^4 where n_0 is the principal quantum number of deuterium. Recent studies [6] [9] [10], indicate that charge transfer collisions between plasma ions in tokamaks and excited states of beam atoms, 'halos' and background thermal atoms cannot be ignored in any quantitative assessment of the CX signature involving Rydberg levels. The appearance of high quantum level ($n=27$) distortions to the X-ray resonance line spectrum from A^{16+} in the ALCATOR-C tokamak for example, has been attributed to CX collisions between excited states of H^0 and Ar^{17+} [10].

The present paper relates to the intensities of the Lyman series of CVI in the absence of the atomic beams in the JET Tokamak. It has been observed that the CVI Lyman decrement becomes 'distorted' when the local influx of D^0 atoms at the boundary is increased [11]. A quantitative account of the changes in the intensities of the CVI Lyman line is attempted in terms of an impurity ion transport code which incorporates the relevant ionisation and recombination (including CX with background thermal D^0) rates for each carbon ion species. Comparison of the predictions of this model with the experimental line intensities allows a derivation of the effective rate coefficients for populating the Rydberg levels of CVI.

2 EXPERIMENTAL PROCEDURE The JET tokamak has a D-shaped toroidal vacuum vessel within which the plasma can be made to adopt a range of boundary shapes and locations [12]. It is relevant to this paper that the plasma can be shifted horizontally inwards along a major radius losing contact with the outer belt limiters and being brought to bear upon the inner wall surface, both limiters and wall surfaces being pyrolytic carbon tiles. On contact with a material surface the plasma releases absorbed D^0 as well as impurities including, of course, carbon. These atomic influxes are registered and qualitatively analysed through their relevant spectral emission [13]. Figure 1 indicates the change in Balmer- α emission and therefore in the influx of D^0 from the inside wall during a 20s JET current pulse.

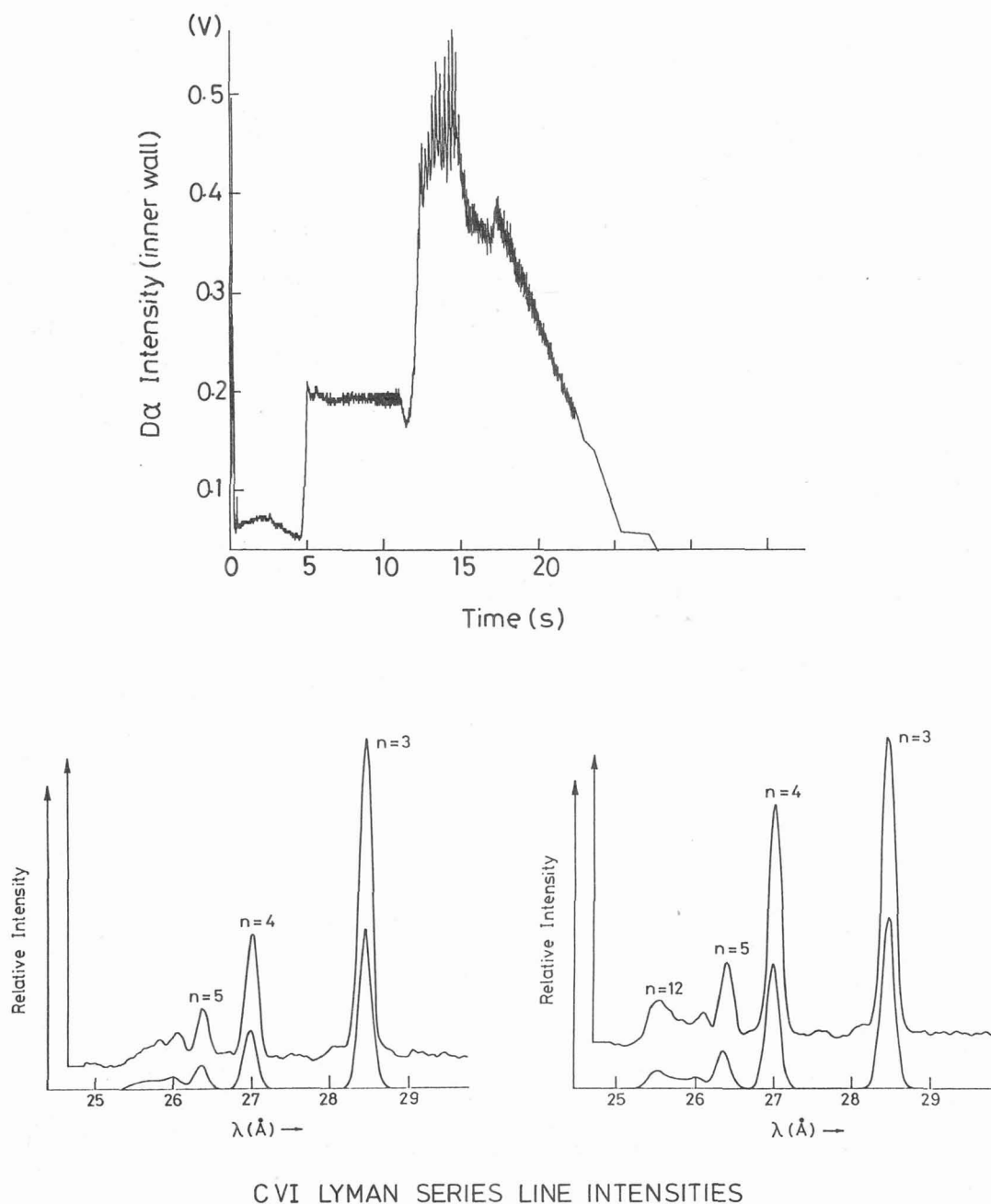


FIGURE 1: Upper curve shows Balmer α intensity from the inner wall during JET discharge #13571. The time-dependent intensity is directly related to the local influx of D^0 at the plasma boundary. The steps in the emission just before 5s and at 11s result, respectively, from a shift of the plasma into contact with the inside torus wall followed by application of an RF heating pulse.

CVI Lyman series line intensities at 3.5s (on left) and at 13s (on right) are shown. Comparison is made between the JET data (upper spectrum) and model calculations (lower spectrum) for each of the two time frames.

Survey spectrometers operating in the VUV and XUV regions of the spectrum [11] view the inside wall along horizontal chords. When the plasma is in contact with the outer limiters (at $t < 5s$, Figure 1) local emission from D° and impurities from the limiter surfaces are not within the line of sight of the survey spectrometers. Essentially therefore, the plasma boundary viewed by the spectrometers is either free of contact with material surfaces (as for $t < 5s$, Figure 1) or in contact with the inner wall, with a consequent large increase in the D° influx (as for $t > 5s$, Figure 1). The further large rise, in Balmer- α of D° (at $t = 11s$, Figure 1) corresponds to application of the RF heating pulse which is associated, characteristically, with increased influxes of both fuel atoms and impurities.

In addition to atomic influx spectroscopy (in the visible region), the VUV and XUV instruments continuously monitor most of the ion stages of the main impurities eg. CIII through CVI. The CVI Lyman series intensities and Balmer α of CVI at 182.2\AA are measured by the XUV spectrometer [11] with a resolution $\sim 0.2\text{\AA}$ (FWHM). During the initial phase ($t < 5s$, Figure 1) when the viewed volume excludes contact between the plasma and a material boundary, the CVI Lyman intensities are in tolerable agreement with the usual electron impact collisional radiative model [14], the calculated Lyman decrement tends to be somewhat steeper than is observed). It is clear however that changes in the Balmer- α emission intensity, when the plasma boundary is shifted and when RF heating is applied (Figure 1), are correlated with 'distortions' to the CVI Lyman decrement and with increased influxes (intensities) of low ion stages eg. CIII. The time-variation of the CVI Lyman series intensities has been deduced taking into account pixel gain fatigue across the micro-channel plate detector. This loss in gain is photon flux dependent and is most problematic at the Lyman- α CVI pixel position. The relative intensities of the remainder of the Lyman series is shown in Figure 1 for two different plasma boundary conditions. The Ly β/γ ratio and the feature at $n = 12$ are the most obvious distortions to the series decrement when the plasma boundary contacts the inside wall.

THEORETICAL MODELS AND COMPARISON WITH EXPERIMENT The radiation shells from each ion species have been calculated using an impurity transport code based on the procedure described in [15]. Simulation of line radiances requires the inclusion of atomic processes as well as the appropriate particle diffusion coefficients. Details of the model assumptions and the input data will be given in a further publication, (Mattioli M et al, to be published). However, a schematic of the plasma parameters at the boundary of a typical JET limiter discharge, showing the concentration gradient of D° , the position of the C^{+5} and part of the C^{+6} shell, is presented in Figure 2. The plasma regions responsible for CX and electronic impact excitation of CVI are indicated.

For the present simulation of the CVI Lyman series intensities it is important to include both the electron impact contribution $C^{+5} + e \rightarrow C^{+5}(n) + e$, and the charge exchange contribution $C^{+6} + D^\circ \rightarrow C^{+5}(n) + D^+$, to the population of the principal quantum levels. The effective rate coefficients, $q_{n \rightarrow 1}^e$ and $q_{n \rightarrow 1}^{CX}$ respectively, include redistributive and cascade effects and are evaluated in a twenty principal quantum shell, n, l, j sub-shell resolved population calculation [16], [7]. An extension to these calculations [16] is required to allow proper treatment of the high Lyman series members of CVI.

Electron transfers from all excited principal quantum shells of deuterium, up to local plasma collision limit of $n(D^\circ) = 5$, have been included in the calculations of the effective CX rate coefficients $q_{n \rightarrow 1}^{CX}$, $n \leq 20$. Low energy transfer cross-sections from the $D(1s)$ ground state are documented [17]. However, there is little data available for CX cross-sections from excited states of thermal D° . As a starting point for comparison with experiment we adopt the Landau-Zener approximation using matrix elements proposed in [18]. Captures from the ground and excited state of D° are assumed to be strictly state selective into the approximate n -shells of CVI. The transfer cross-sections peak at n -shells of CVI which are almost linear multipliers of $n(D^\circ)$, ie. at $n(D^\circ) \hat{n}$. The l -distributions are assumed as for capture into \hat{n} .

It is recognised that the simplified Landau-Zener (LZ) rate coefficients tend to be too low. They do have the merit of addressing the problem in terms of the details of molecular potential curve pseudo-crossings which is appropriate to the present low collision speed regime and to more refined calculations. Comparison of experiment with the model, indicates that the theoretical effective (LZ) rates need to be increased by factors of between 1.5 and 3 depending on the CVI quantum level, Figure 3. The empirically adjusted $q_{n \rightarrow 1}^{CX}$ come closer to the values predicted by an overbarrier model [19] which is expected to give $q_{n \rightarrow 1}^{CX}$ factors of 4-5 times the LZ model. The probability is that the CX cross-sections lie between the predictions of the two theoretical models. New direct capture cross-section calculations are in progress to check the validity of these conclusions. However, it is abundantly clear that, whatever the absolute cross-sections, all the unsmeared levels in the donor atom contribute to the charge-exchange signature of the recombined ion.

The absolute concentration of $D^0(r)$, Figure 2, has been used as a 'free' parameter in a comparison between the transport model prediction and the observed CVI line radiances. The radial variation of D^0 with plasma radius is assumed to be functionally similar to that predicted in [20]. The absolute concentrations of $D^0(r=a)$, where 'a' is the inner-wall plasma boundary radius, differ by a factor ~ 50 between the outer limiter ($t=4s$) and inner wall ($t=13s$) phases of the JET discharge. This is, within factors of two, the same as the time variation of the D^0 influxes, Figure 1.

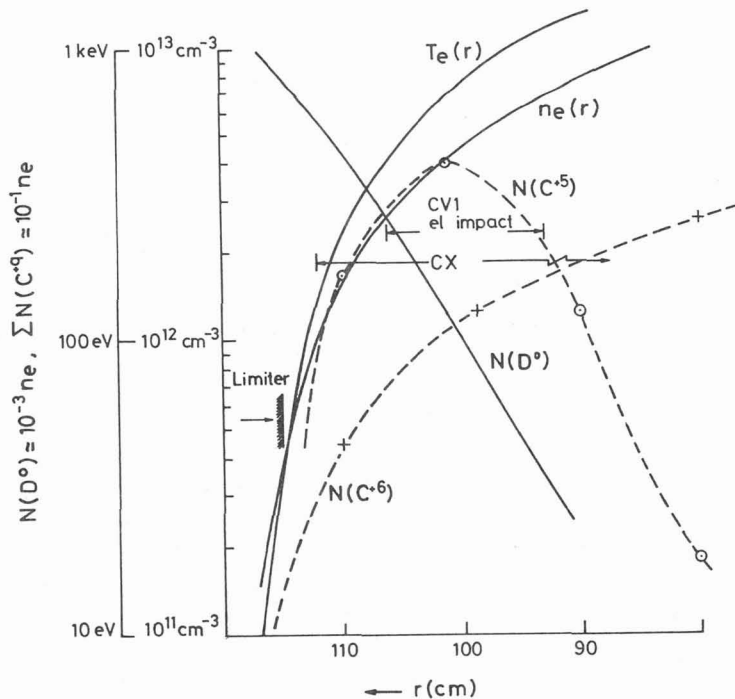


FIGURE 2: Schematic representation of the limiter boundary region of a JET plasma. The radial variation of the electron parameters and of atomic deuterium are indicated. This data is used as input to an ion transport code which predicts the radial shells of carbon ions. The location of the C^{+5} ions and part of the C^{+6} shell are shown with the regions which contribute, through electron impact and CX, to the CVI Lyman series intensities.

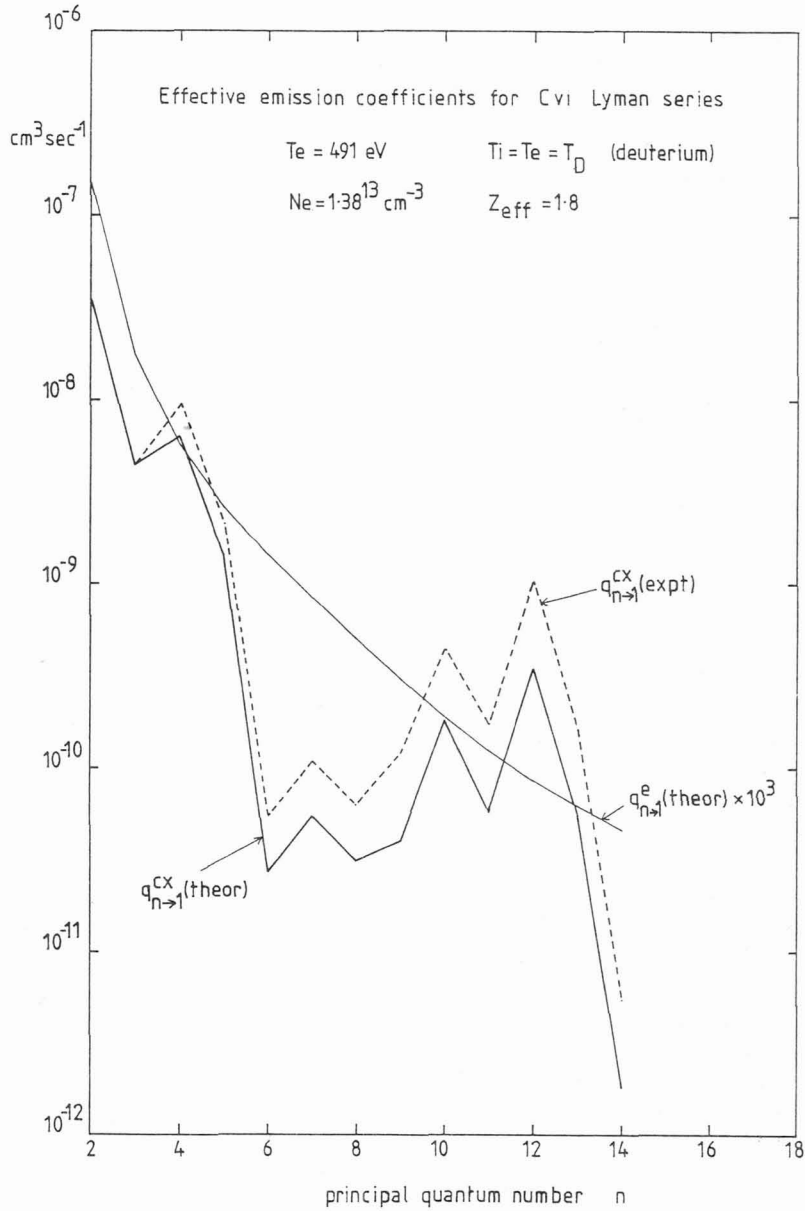


FIGURE 3: Effective Emission Coefficients of C VI Lyman series for appropriate local boundary parameters in JET. The solid curves represent the effective coefficient for electron impact $q_{n \rightarrow 1}^e$ and charge exchange $q_{n \rightarrow 1}^{CX}$. The dashed curve is the deduced CX coefficient after comparison of the model calculations with the observed spectrum.

CONCLUSIONS The relative intensities of the Lyman series of CVI from a tokamak are sensitive to the plasma boundary conditions and in particular to the concentration of atomic species of the working gas (D_2). In the absence of neutral D^0 , the CVI Lyman series intensities are adequately described by electron impact excitation from the CVI ground state.

When there is an appreciable influx of D^0 at the plasma boundary, charge exchange collisions between D^0 and C^{6+} populate preferentially high n -states and result in 'disortions' of the CVI Lyman decrement.

The CVI Lyman series intensities have been simulated using an impurity ion transport code which includes, for calculation of the CVI Lyman intensities, effective emission coefficients for electron impact excitation of CVI and for charge exchange between C^{6+} and all levels of D^0 up to $n=5$, the 'collision' limit. Cascade decays of the CVI levels are taken into account in the calculations of the effective atomic rates. The charge exchange cross-sections are calculated using a Landau-Zener model.

Comparison of the model with the observed CVI radiances indicates plausible corrections to the simple theoretical model for the charge exchange cross-section as a function of principle quantum state.

The contributions from charge exchange to the effective emission coefficients for the CVI Lyman series are in semi-quantitative agreement with changes in the observed D^0 influx at the plasma boundary. The observations offer a potential method of measuring the concentration of D^0 near the boundary of a fusion plasma.

Other effects associated with a change in the deuterium influx include the intensity ratio of the triplet/singlet resonance lines from the $n=2$ levels of CV (increasing from 0.45-0.65 typically, for factor of 10 increase in the D^0 influx) and the Balmer α /Lyman β ratio of CVI (a factor of two increase typically, for factor of 10 increase in the D^0 influx).

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