1.0 Introduction

The spectroscopic measurement and monitoring of impurity radiation in tokamak plasmas has not only led to key advances in the diagnosis of fusion plasmas, but has also contributed to our understanding of the behaviour of atomic processes and populations in a wide range of novel environments.

A typical tokamak plasma consists mainly of electrons and deuterons together with a small concentration of impurities[1,2]. The presence of such impurities gives cause for concern. As tokamak plasmas are heated to high temperatures and confined for times required to meet the Lawson criteria[3], the plasma impurities radiate energy through the emission of spectrum lines and bremsstrahlung radiation, modifying the plasma resistivity as well as their own sources from the vessel walls and the divertor target plates. Thus they produce many effects, often unwanted, which require a detailed knowledge of impurity concentration for their evaluation.

The current method of attempting to control plasma impurities is by employing divertor configurations to channel the scrape off layer plasma to remote target plates. The divertor essentially acts as an exhaust system to assist with the removal of impurities from the bulk plasma[4] as well as inhibiting removed impurities returning to the confined plasma. These environments add to the demand for the development of advanced spectroscopic methods which can measure impurity ions with greater accuracy.

1.1 Active and passive spectroscopy

The application of spectroscopy to monitor plasma impurities can be categorised as either passive or active. Passive spectroscopy involves exploiting the natural emission from impurity ions or atoms in the thermal plasma, where as active spectroscopy involves perturbing by external means the ions or atoms contained in the plasma so as to enhance or alter their emission. The latter is potentially the more accurate diagnostic procedure. Spectroscopy is not only confined to the study of impurity concentrations in fusion plasmas, but important quantities such as the plasma temperature and the electron density are also of interest. In the following sections we show examples of both active and passive spectroscopic methods

1.1.1 Passive spectroscopy

Typical quantities which may be measured using passive spectroscopy include the electron density and electron temperature from spectral line ratios, the effective ion charge of the plasma as well as the impurity concentration and impurity fluxes from absolute intensities and ion temperatures from line widths.

If we first consider the use of spectral line ratios, a common method involves exploiting the emission due to dielectronic satellite lines associated with plasma impurity ions[1,5], see figure 1.1.

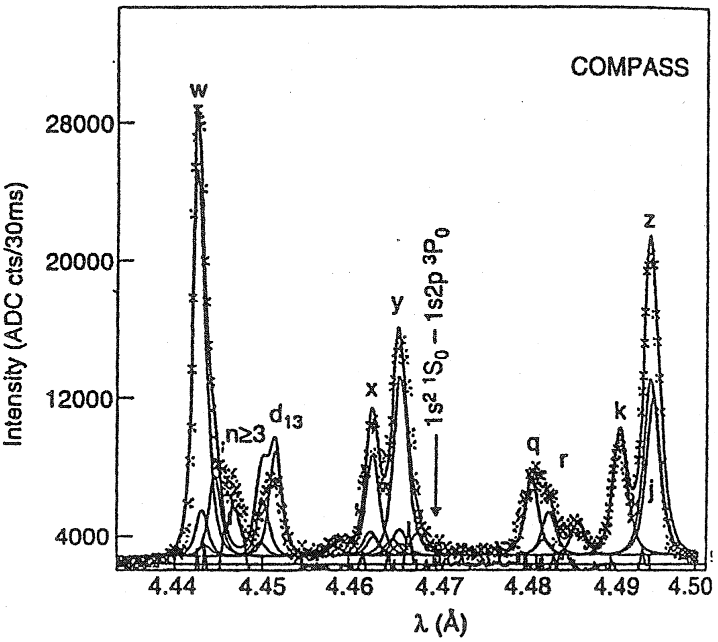


Figure 1.1 Spectral emission due to dielectronic satellite lines of He-like Cl XVI from the COMPASS experiment. The electron temperature is obtained from the ratio of the lines w and k. The diagram was taken from [5] where a detailed discussion can be found.

The satellite lines arise due to radiative stabilisation following resonance capture in the process of dielectronic recombination. As discussed by Coffey et. al.[5], the electron temperature can be obtained from the ratio of the lines denoted by the labels w and k. Also from the width of the w line the associated ion temperature can be inferred. The widths of passive emission lines can also be used to measure the electron density via Stark broadening. A recent example reported by Terry et.al.[6] and later by Meigs[7], involves utilising the high-n Balmer series, see figure 1.2.

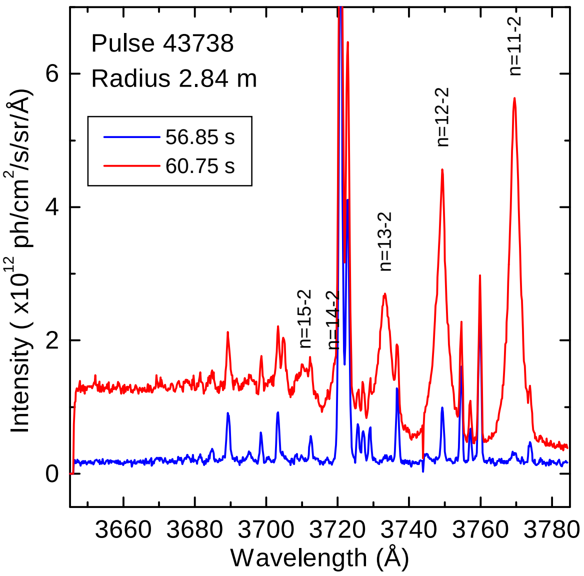


Figure 1.2 Spectrum of the high n-Balmer series for deuterium, courtesy of Dr A. G. Meigs[7]. The Stark widths of the high-n Balmer lines can be used to infer the electron density. The average electron density for low recombination (56.95 s) is approximately 2.3 x 10^{19} m^{-3} and 3.5 x 10^{19} m^{-3} at high recombination (60.75 s).

The high-n Balmer series arises due to the dominant role of recombination in low temperature and high electron density environments.

Focusing on the passive measurements associated with impurity ions. The excitation and ionisation state of emitting impurities is almost entirely electron impact driven. Also the interpretation is complicated by the non-localised nature of the emission. Figure 1.3 shows a BeII feature typifying the experimental data used for analysis of influx. More complicated inferences such as the recycling of neutral hydrogen diffusing into the edge of the plasma has also been attempted. This is achieved by exploiting the emission from impurity ions themselves following the capture of an electron via thermal charge exchange[1,8],

$$X^{+Z0} + D_{edge} \rightarrow X^{+(Z0-1)} + D^{+}_{edge} \qquad 1.1$$

Thermal charge exchange usually occurs at the edge of the plasma where the conditions are such that hydrogen isotopes can act as donors to partially ionised impurity ions[8]. The thermal charge exchange emission from CVI and CIII impurity ions is also shown in figure 1.3.

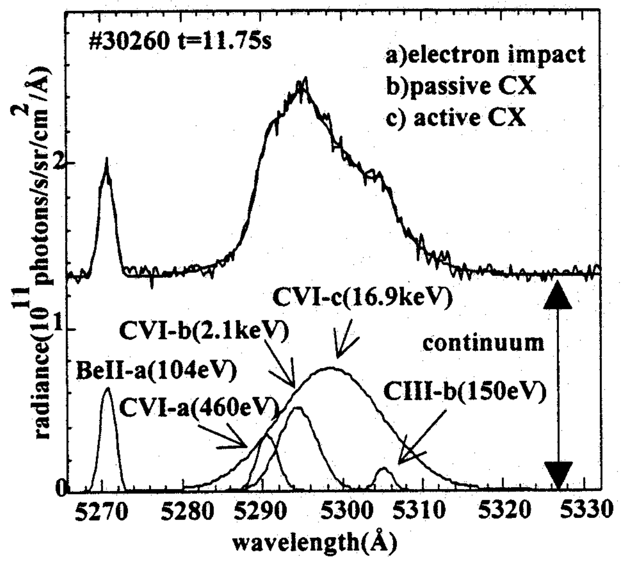


Figure 1.3 Thermal charge exchange spectrum showing the emission from CVI(n=8-7) and CIII(n=7-5) impurity ions. Also shown is the contribution to the spectrum due to a) impact excitation, and c) active charge exchange emission. The diagram was taken from [8].

Finally, the effective ion charge of the plasma, which is a measure of the total impurity content of the plasma, can be obtained from passive measurements of the bremsstrahlung radiation[9].

1.1.2 Active spectroscopy

Active spectroscopy as mentioned earlier, is not only more accurate but can be employed to measure a range of parameters which are not readily accessible using passive spectroscopy. Techniques such as pellet injection, gas puffing and Laser ablation[10] can all be used to study the impurity transport of the plasma. The active introduction of trace impurities into the plasma is not only confined to the study of transport parameters, quantities such as the electron density and temperature can be measured using line ratio techniques during gas puffing experiments[11]. However the most fruitful active diagnostic method arises from the injection of neutral atomic beams into the plasma.

Neutral beam injection can be employed to investigate the edge as well as the core of the plasma. As an edge diagnostic, slow neutral helium[12,13] and lithium beams[14] are often employed to measure the edge electron density and temperature, while fast neutral helium and deuterium beams, which penetrate into the core of the plasma, can be used to measure a wide range of parameters[15,16,17]. Confining ourselves to fast beams, neutral deuterium beams can be exploited as diagnostic probes to measure the concentration and temperature for a wide range of impurity ions using active charge exchange spectroscopy[18]. Active charge exchange involves measuring the emission from impurity ions following the capture of an electron from the beam atoms,

$$X^{+Z0} + D(1s)_b \rightarrow X^{+(Z0-1)} + D_b^+ \qquad 1.2$$

The impurity ion density can then be recovered from the recorded charge exchange emission using the relation,

$$n_{z_0} = \frac{4\pi \int \Phi_{CX}(\lambda) d\lambda}{q_{cx} \int n_b ds} \qquad 1.3$$

where Φ_{CX} is the charge exchange emission flux, q_{cx} is the effective emission coefficient[19] and $\int n_b ds$ is the line integrated beam density. The ion temperature can be obtained from the width of the Doppler broadened emission line in the usual manner. We show in figure 1.4 an example of a deuterium beam active charge exchange spectrum.

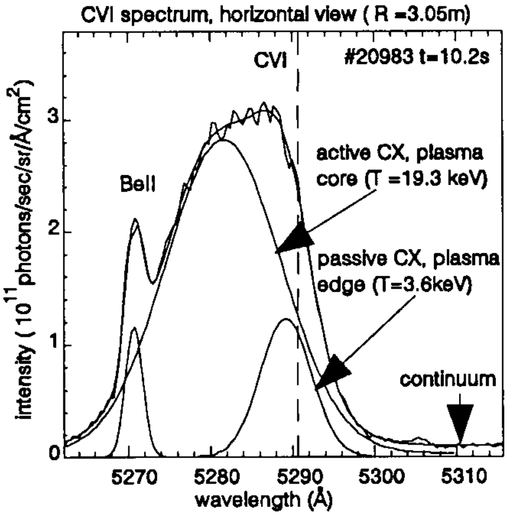


Figure 1.4 Deuterium beam active charge exchange spectrum for CVI at 5290 Å (T=19.3 keV), also shown is the passive emission spectrum. This diagram was taken from [16] where a full description of the spectrum is given. The CVI concentration is obtained from measuring the total charge exchange flux. The temperature is obtained from the width of the Doppler broadened line.

Active charge exchange spectroscopy provides an accurate and localised measurement of the plasma impurity densities. However the accuracy at which the impurity concentration can be measured is governed by the accuracy at which the neutral beam density is known.

The most common approach to determine the neutral beam density is to employ a simple attenuation calculation which takes into consideration the atomic processes which contribute to ionising the beam atoms[16]. However it is now possible, in principle anyway, to accurately measure the neutral beam density using Balmer-alpha beam emission spectroscopy[20]. As the neutral deuterium beam atoms penetrate into the plasma, before they are ionise they become temporarily excited and as they relax their emission contains information regarding the population of the n=3 shell of the beam atoms. The neutral beam density can then be recovered from the beam emission spectrum using the relation,

$$n_b = \frac{1}{n_e}\left(\frac{\Phi_{D-\alpha}}{q_{D-\alpha}}\right) \qquad 1.4$$

where $\Phi_{D\text{-}\alpha}$ is the total flux of the beam emission spectrum, n_e is the electron density and $q_{D\text{-}\alpha}$ is the theoretical Balmer-alpha effective emission coefficient. In working plasmas the situation is complicated. The beam atoms experience an electric field within their own frame of reference as a result of moving with a velocity through the confining magnetic field of the tokamak. The influence of the electric field is to remove the degeneracy associated with the energy levels of the beam atoms. This gives rise to a Stark resolved energy level structure and the beam emission spectrum is observed as a series of Stark components, see figure 1.5.

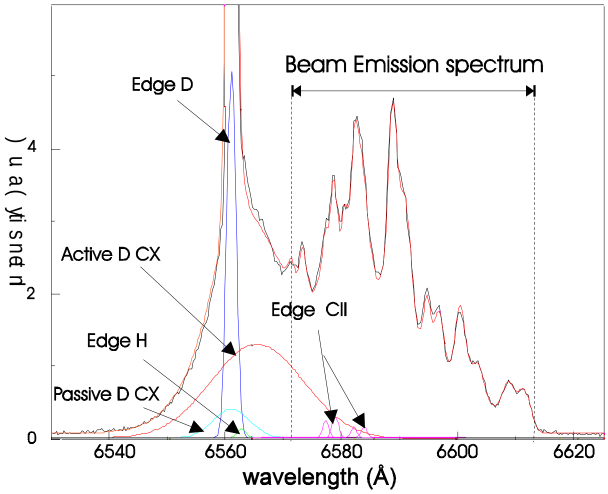


Figure 1.5 Beam emission spectrum for a high power double beam bank pulse from the JET experiment. The beam emission spectrum is a complicated array of Stark components which overlap each other. Also shown are the active and passive charge exchange signals which are in the spectral vicinity of the beam emission spectrum.

Turning our attention to the use of fast helium beams. A neutral helium beam can be used to measure the impurity concentrations and their associated temperatures in the same manner as with a fast neutral deuterium beam. We show in figure 1.6 an example of a helium beam active charge exchange spectrum.

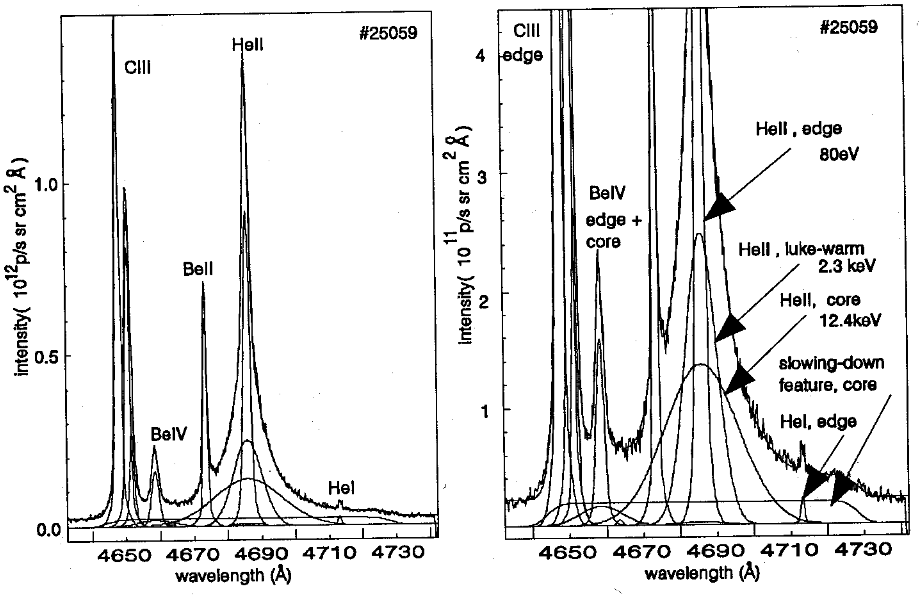


Figure 1.6 Helium beam active charge exchange spectrum. The figure on the left gives a general over view of the features contained within the observed spectral region. The figure on the right is an expanded figure showing thermal and non-thermal components. These figures were taken from [16] where more information can be found.

There are however significant benefits of using a neutral helium beam rather than a fast deuterium beam as a diagnostic probe. The most practical benefit involves reducing the generation of neutrons during plasma operation. A fast neutral deuterium beam contributes to producing neutrons via the beam-beam and beam-plasma interaction[21]. These unwanted neutrons contribute to activating the experimental vessel as well as complicating the analysis of the neutron flux signals from the bulk plasma. Using a neutral helium beam (^{3}He) removes this problem since the contribution to the neutron production due to the beam-beam and beam-plasma interaction is very small.

There are also diagnostic benefits, the most obvious concerns the detection of alpha particles via the resonant process of double charge exchange[22]. More interestingly though, is the new diagnostic capabilities which may arise due to the presence of metastable levels in the beam atoms. If the He(2 ^{3}S) metastable is significantly populated it may act as a charge exchange donor. Preferential charge exchange between the ground state and the He(2 ^{3}S) with different plasma impurity ions may be possible. This would lead to a more flexible charge exchange diagnostic.

It should be noted though that the use of a fast neutral helium beam is very much still in its infancy. There are many issues which require some investigation. For example, what happens to the metastable population as the beam traverses the plasma?, what is the behaviour of the excited state population structure?, and do the metastables levels contribute significantly to the beam attenuation?. The application of beam emission spectroscopy with a neutral helium beam also requires some attention. It is expected that the lines associated with the n=3 to 2 shell for both spin systems can be of immediate diagnostic use[23]. A more interesting aspect concerns the excited levels of the beam atoms where the Lorentz electric field results in the formation of forbidden lines. These lines may be of use to infer the internal magnetic field of the plasma[24]. However extensive spectroscopic observations are still required to explore the diagnostic potential of the helium beam emission spectrum.

1.2 Aim of this work

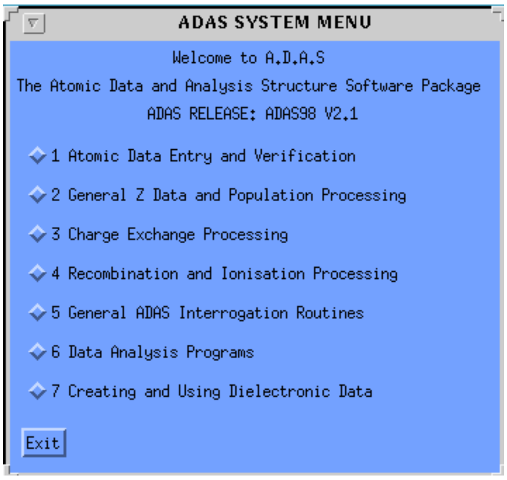
There are two main topics which we address in this work. The first involves measuring the neutral deuterium beam density at JET Joint Undertaking[25] via beam emission spectroscopy. The primary aim is to be able deduce the neutral beam density for high power double beam bank pulses on a reliable basis. Continuing along this theme we also consider the evaluation of the neutral beam density using a numerical attenuation calculation. To achieve the former and latter we employ a bundled-nS collisional-radiative model to evaluate effective stopping and Balmer-alpha emission coefficients. We also aim to show the parameter dependencies of these coefficients and the underlying role of the atomic processes which contribute to the attenuation and population redistribution of the neutral deuterium beam atoms. A comparison is then made between the numerical attenuation calculation and the results obtained from the spectroscopic measurements.

The second topic which is of concern involves modelling the attenuation and the excited state population structure of a fast neutral helium beam. To address some of the uncertainties with regards to a fast helium beam we have developed a bundled-nlSL collisional-radiative model. This model is employed to investigate the behaviour of the excited state population structure, the evolution of the metastable populations and the beam attenuation. Effective cross coupling coefficients are also calculated and their parameter dependencies are explored.

During the course of this work, computational tools designed to archive and study the global behaviour of the derived atomic data for both neutral deuterium and helium beams have also been developed. These programs, together with the bundled-nlSL model, have been written for general use within the Atomic Data and Analysis Structure package, ADAS.

1.3 Atomic Data and Analysis Structure

The Atomic Data and Analysis Structure package[26] is a collection of programs and databases which have been designed to assist with the modelling and analysis of spectral observations from fusion and astrophysical plasmas. There are three main components of the ADAS system. These include a suite of interactive programs, a collection of fundamental and derived atomic databases and a library of FORTRAN routines. If we first consider the interactive programs. The ADAS package consists of seven different series of modelling codes, each of which addresses different areas of atomic physics. In any given series there are a number of individual programs. Each of the programs are driven by an IDL interface while the main calculation is done using a FORTRAN routine which is 'spawned' from the IDL. The main interface of ADAS can be seen in figure 1.7.



Welcome to A.D.A.S
The Atomic Data and Analysis Structure Software Package
ADAS RELEASE: ADAS98 V2.1

Figure 1.7 Snap shot of the main IDL interface of the Atomic Data Analysis Structure Package.

The processing screen contains an array of toggle buttons which correspond to each of the series of modelling codes. If the user activates a button, the menu corresponding to the list of programs for that particular series will appear. As an example we show in figure 1.8 the menu for the series three programs.

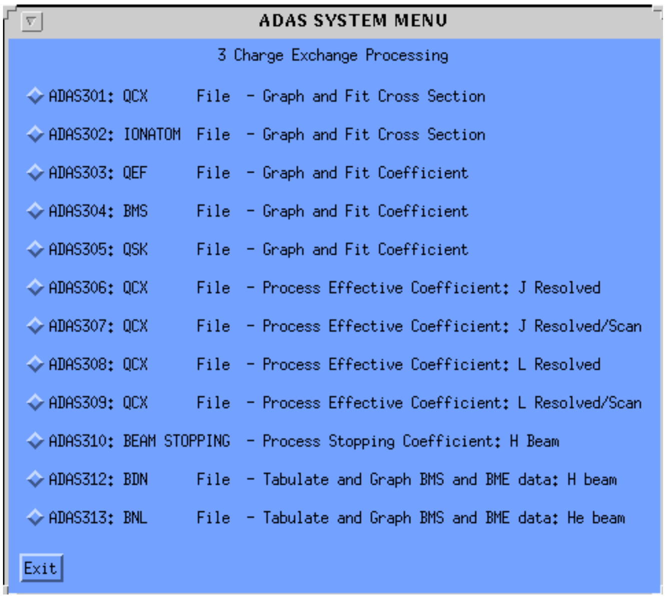


Figure 1.8 Snap shot of the series three menu system.

If the user then activates any of the toggle buttons a series of interactive panels will guide the user through the calculation of interest.

Focusing on the derived and fundamental atomic databases of ADAS. There are a total of twenty six databases, each of which are archived according to an ADAS data format prescription[26]. To distinguish each database they are individually assigned an ADAS data format number e.g. adf21. The fundamental atomic databases are based on extensive compilations of the best available experimental and theoretical data, while the derived atomic databases contain the output from the modelling codes of ADAS and are conveniently stored in a format to be of direct use to experiment.

The last component of the ADAS system is the library of FORTRAN routines[27]. These routines are designed to allow the user to access the fundamental and derived atomic databases for their own application. Also there are routines which evaluate quantities which may also be of interest for individual applications.

1.4 Format of thesis

We begin in chapter 2.0 by describing the physical conditions of tokamak plasmas and the atomic processes which contribute to the attenuation and the excited state population structure of neutral deuterium and helium beam atoms. We also discuss in detail the collisional-radiative approach of modelling beam attenuation and emission, which is the method adopted in this work. A brief literature review of previous work is also given.

Chapter 3.0 outlines the application of collisional-radiative theory in the form of the bundled-nS deuterium beam model and the more elaborate bundled-nlSL helium beam model. The computation implementation of each of these models are discussed within the context of ADAS and an account of their operation and validation is also given.

A detailed study of the parameters dependencies of the effective stopping and Balmer-alpha emission coefficients for a deuterium beam is the subject of Chapter 4.0. In this chapter we also discuss the archiving and the rapid assembly of the effective coefficients for experimental analysis. This chapter serves as a preamble to chapter 5.0 which details the application of the bundled-nS model in an attempt to exploit the beam emission signature at JET Joint Undertaking. The spectroscopic deduction of the neutral beam density using the beam emission flux and the Balmer-alpha emission coefficients is the topic of interest here. The evaluation of the neutral beam density using the theoretical beam stopping coefficients is also of concern.

In chapter 6.0, using the bundled-nlSL model we investigate the parameter dependencies of the collisional-radiative coefficients and the equilibrium excited state populations. We also investigate the implications of neglecting the metastable nature of the He(2 ^{1}S) and He(2 ^{3}S) levels while evaluating their population. A study of the attenuation of a fast neutral helium beam, while altering the initial metastable content on entry to the plasma, is also undertaken. A summary and discussion regarding the contents of the thesis is then given in Chapter 7.0.