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JET spectra and their interpretation

ABSTRACT

The scope of spectroscopic diagnostic studies on the JET tokamak is summarised. The atomic data and modelling required to analyse JET spectral observations are illustrated by some case studies.

INTRODUCTION

Spectroscopy on JET is committed to interpretative diagnostics for fusion plasmas. The theoretical modelling necessary to achieve these ends requires extensive atomic data, including energy levels and oscillator strengths, but especially electron-ion, ion-ion and ion-atom collision cross-sections. In keeping with this meeting, however, it is atomic structure and the spectra themselves which are emphasised. It is intended to provide an overview of the areas of current excitement, an outline of the reduction methods used and of the atomic data exploited.

Within the constraints of the fusion objectives, a flood of spectroscopic data is available at JET which, in principle, can be accessed together with other extensive diagnostic information in the JET database. At this time, more than 20000 pulses each with about 12 Mbytes of information have been recorded and a rich phenomenology has been observed. It is apparent that many features of such large volume, strongly heated fusion plasmas of the JET type are somewhat different from those of the familiar/idealised high temperature low density plasmas of the astrophysical type. The reasons are evident, namely:- powerful influence from interactions with the limiting surfaces of the plasma; high neutral deuterium presence due to neutral heating beams and recycling from boundary surfaces; a confining magnetic field which can be configurated to create plasma zones of different diffusive character; transient perturbation of the plasma by pellet injection and gas puff; active feedback control of selected plasma parameters.

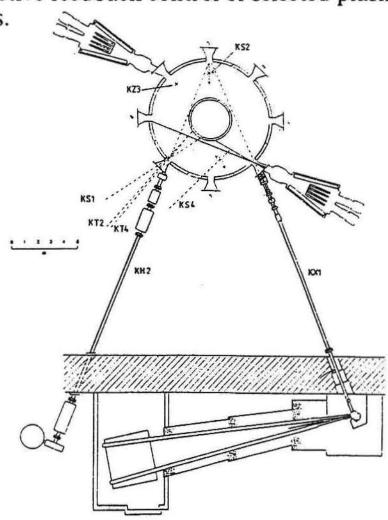

Fig. 1. A plan view of JET with the lines of sight of the principal spectrometers indicated. Note the two neutral deuterium beam injector (NBI) assemblies.

The characteristics of the various spectrometers are summarised in table 1. There are approximately fifty further diagnostics including various techniques for measuring the electron parameters $n_e(r)$ and $T_e(r)$ (LIDAR Thomson scattering, ECE , interferometry, reflectometry), infrared cameras, x-ray camera diode arrays allowing tomographic reconstruction in the poloidal section at very high time resolution etc.

Table 1. Characteristics of principal spectrometers.

Beam diagnostics		
KS4	4000-7000A	multi-chord
KS5	4000-7000A	multi-chord fibre optic link
Edge diagnostics		
KT3	4000-7000A	several lines
Spatial scan spectroscopy		
KT1	100-2500A	grating
KS2	1-24A	2-crystal
KT4(1/2)	10-340A, >2000A	grazing incid.
Survey spectroscopy		
KS1	1-24A	
KT2	100-1700A	grating
High resolution spectroscopy		
KX1	1-3A	bent crystal
Other		
KH2	>4kev	Pulse height
KZ3		laser ablat.

A more limited set of radiation protected spectrometers will be available in the active (deuterium / tritium) phase of JET operation.

NBI together with ion cyclotron resonance heating (ICRH) supplement the direct ohmic heating of the plasma by the induced toroidal current in the tokamak. Combinations of the plasma heating methods, control of the position and elongation of the plasma in the poloidal section, vessel conditioning, control of internal instabilities and X-point operation have achieved the plasma parameters in table 2. X-point refers to the operational mode in which a poloidal magnetic field null is created within the vessel so separating the plasma from material limiters. τ_E and τ_i are respectively the energy and particle confinement times. Q_{D-T} is the predicted ratio of the total thermonuclear power output to the power input if the deuterium in the plasma were to be replaced by a fifty per cent mixture of deuterium and tritium.

Table 2. Selection of plasma parameters.

Param.	Achieved	Range
I_p	7 MA	< 5MA X-point, 7MA limiter
P_{tot}	35 MW	< 7 OH, < 18 ICRH, < 21.5 NBI
T_e	12 keV(centre)	< 12 keV
T_i	25 keV(centre)	< 25 keV
N_e	2.8×10^{14} cm^{-3}(centre)	10^{12}-2×10^{14}
Zeff	1.3	1.5 - 6.0
τ_E	1.2 sec(global)	0.2-1.2 sec
τ_i		< 3.0 sec
Q_{D-T}	0.2-0.5 !	

The vessel, composed of the alloy Inconel, is protected at the inner wall of the torus by graphite tiles and at the outer wall by two graphite toroidal belt limiters. Further graphite tile protection is present especially at the top and bottom of the vessel for single and double null X-point operation. There has been a policy of carbonising the vessel interior by discharges in methane. This trend to light impurity contact materials is continuing. Presently beryllium evaporators are in use. The oxygen gettering effect of beryllium and other benefits of the beryllium coating appear quite marked and there is an intention to use beryllium as the material for limiters and antennae screens in the near future.

Table 3. Principal fractional impurities relative to n_e and their sources.

Impurity	Conc.	Source
He	arbitrary	initial gas fill
Be	< 0.01	evaporators-- > walls & limiters.
C	0.05	limiters,inner wall, X-pt. strike pts.
O	0.01	walls, limiters
Ni	< 0.001	antennae screens, walls
Cl	< 0.007	uncertain
Ne,Ar,Kr	arbitrary	gas puff
Fe,Ni,Mo, etc.	arbitrary	laser ablation

A general description is given in the JET Annual Reports (Keen, 1987) (see also Schumacher et al.,1989; Pasini et al.,1988; Bartirómo et al., 1989)

SPECIFIC SPECTRA AND STUDIES

Table 4 itemises the various spectroscopic studies carried out, their fusion related objectives and the specific atomic data adopted. The purpose is to draw attention to the atomic data in use and to indicate the paths along which the JET spectroscopic studies are likely to evolve. It will be evident where particular weaknesses exist or new data will be required. Limitations in space allows illustrations in only three areas which have been particularly active in the recent JET program.

CXRS & ABAS - a new spectroscopy

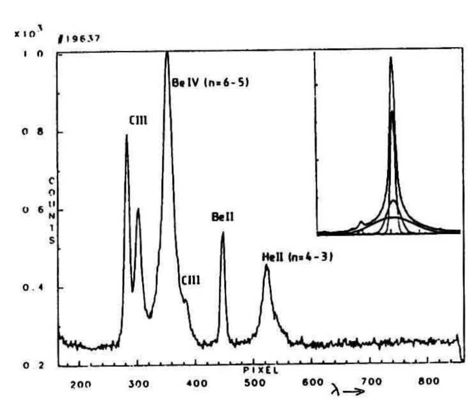

Fig. 2. Charge exchange signals from BeIV & HeII. Insert illustrates resolution of HeII line into hot (central) beam induced CX part and cold (edge) part

It is perhaps surprising to begin with observations of hydrogen (in fact deuterium in JET) and hydrogenic ions of low z, since from an atomic structure point of view, little has been added for many years. Nonetheless emission from such low z hydrogen-like ions has revolutionised the spectroscopic diagnostic capability for fusion

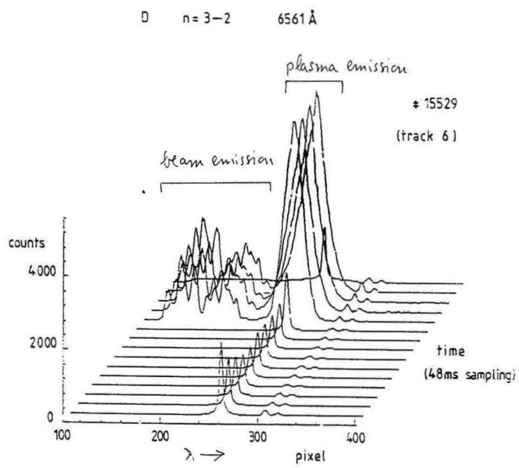

Fig. 3. Dα in the vicinity of 6561A showing plasma and beam emission.

plasmas. Strong O^{+7} emission is common in many plasmas, but not so common at temperatures of order 15keV and in the n=10-9 transition. The reason is of course neutral hydrogen beams. Figure 2 is a very recent spectrum from JET and illustrates spectra influenced by charge exchange from neutral deuterium (E=40keV/amu) in the heating beams. In the absence of beams, both HeII and BeIV show only narrow features similar to that of BeII and originating in the cold plasma periphery (T_e of order 100-500eV). The observed widths in figure 2 arise from hot component emission from the beam/viewing line intersection following capture by the corresponding bare nuclei. The hot feature separated from the cold 'edge features' allows diagnostics of light impurities in the plasma centre where they are normally fully ionised. Its width and displacement gives the ion temperature and plasma rotation. Exploitation depends on confident subtraction of the cold components and the bremsstrahlung background. For HeII, the cold feature arises from at least two populations which evolve during the neutral beam heating period. The shape of the hot feature at high plasma temperature is modified by the variation of the charge exchange cross-section with energy. Evidently the analysis procedures are improved by exploiting passive viewing lines (which do not intersect the beams), calibrating observations using the unviewed beam line and pulsed operation of the beams. Theoretical modelling of the effective emission coefficients allows reduction of the calibrated line of sight emissivities of the hot feature to an emission measure. The deduction of the effective coefficients is complicated by the n-shell distribution of charge exchange capture and its energy dependence, redistribution by collisions and Lorentz fields, cascade, fractional energy components in the beam and capture from excited states of deuterium. With the additional knowledge of the beam attenuation with path length, the emission measure of the observed volume can be resolved to a local impurity density. Such procedures termed 'charge exchange recombination spectroscopy' (CXRS) are practised at JET for He, Be, C and O -the primary light impurities (Boileau et al., 1989a,b).

Similar observation for deuterium itself is illustrated in figure 3 before and during beam injection. The Balmer alpha features become very complex during injection. Their exploitation has been termed 'active Balmer alpha spectroscopy' (ABAS). The hot and cold components at the unshifted wavelength have the same interpretation as before although the cold part is complicated by recycling deuterium from limiters which can penetrate quite deeply into the plasma and so have a relatively high temperature. The blue displaced emission is from the deuterium in the beam. The Doppler displacement follows from the beam/viewing line inclination. There are three components due to full, half and third energy fractions in the beam. Each of these is resolved into Stark components of π and σ polarisation by the large vxB electric field (of order 10^5 V/cm) arising from the cross-field motion of the beam particles. Because of the beam speed, the excitation is primarily by positive ion impact. These observations have huge diagnostic potential. Precise geometry is checked by the net Doppler displacements, the π and σ separations give the projected internal magnetic field. The variation of the signals along the beam path measures the beam attenuation and the differential attenuation with beam energy. The composition of the beams at source is also revealed. Zeff may be derived from the ratio of the Stark to main charge exchange feature ratio and is to an extent calibration independent. Clearly the interpretation is strongly dependent on accurate fundamental cross-section knowledge with particular sensitivity to beam stopping data (Boileau et al., 1989c).

On the other hand the transition probabilities and energy levels are well known. However the range of such observations is expanding rapidly. Similar high n-shell emission following charge transfer has been observed for He-like (Rice et al., 1987), Li-like, Na-like and K-like ions.(eg Si^{+13} n=11-10,..,15-14; Kr^{+25} n=16-15,..,23-22; Kr^{+17} n=15-14 - Hofmann (1989)). The Rice results followed capture from thermal hydrogen.

Table 4. Summary of energy and transition probability data usage at JET.

Primary area	Secondary area	Tertiary area	Study	Illustration	Energy & transition probability data	Sources & Comments
Edge plasma	Visible spectroscopy	Influx of light impurities from limiters	Deduction of suitable lines & S/XB ratios for BeI, BeII, CI, CII, CIII, OII, OIII	1. OII(4351A) & Dγ relative intensities JET pulses #10353, #10354	n = 3-3 & 4-3 A-values; 2-electron transition probs. from n = 3; cascade paths from n < 7	mostly reasonably known - some exceptions
		Influx of metal. impur. from limiters	Deduction of suitable lines & S/XB ratios for CrI, CrII, FeI, FeII, NiI, NiII	2. CrII(2835-2862A multiplet) JET pulse #2470	Association of lines with metastables; A-values; branching to to different metastables; parent mixing	Kurucz(1972), Johannson(1987), Litzen(1987), Hibbert(1988) - uncertain!
		Fluxes of light & med. impur. in divertors	As (2) above, extended to include AlI, AlII, SiI, SiII Density dependent corrections	3. not available	not determined	probably available
		Fluxes of high z elements in divertors	As (2) above, extended to include MoI, MoII, WI, WII	4. not available	not determined	quite uncertain!
		Thermal deuterium	Evidence of CX from excited states of D to fully ionised and helium- like ions	5. Composition of CVI (5290A) cold feature (see refs.)	Energies of high nl levels of lithium-like ions in terms of polarisabilities	well known - Edlen.
		Molecular species	Direct evidence for chemical sputtering; states & kinetic energies of atomic/ionic constituents after dissociation Equivalent approach to S/XB ?	6. CH band spectrum (fig. 10.)	Suitable bands for CH_n, CH^+, OH, H_2, BeH etc; emission & dissociation probabilities - uncertain requirements	not investigated - uncertain
	VUV & EUV	Thermal hydrogen	Evidence of CX from ground & excited states of D to stripped impurities	7. CVI Lyman series, inner wall discharge JET pulse #13751	well known	
			Evidence of CX from ground & excited states of D to partially stripped light impurities	8. CIII disruption spectrum in KT4 JET pulse #11011	Radiative &/or Auger probabilities for 2snl & 2pnl ($2 < n < 6$); state selective dielectronic coeffts.	Mostly known; Badnell(1986) for Auger/diel
		Radiated power by heavy species in divertors	Stages, radiat. power, observable spectral features for 10-200 eV plasma. Shell group / pseudo - band structure approach ?	9. MoIII - MoXII transition arrays (fig. 9.)	Energies & A-values for describing integral emission of pseudobands and shell-shell ionis./recom. Mo, W	uncertain - Klapisch , Cowan ?
		ion/surface interaction	Secondary electron emission by impact of highly ionised ions on graphite & metal surfaces	10. not available	Radiat./Auger probs. & cascade paths for multi - spectator & strongly correl. neutralisation for Be^{+4}, C^{+6} etc.	unknown

Primary area	Secondary area	Tertiary area	Study	Illustration	Energy & transition probability data	Sources & Comments
Bulk plasma	Visible spectroscopy	Bremsstrahlung emission	Deduction of local Zeff	11. Zeff variation radially across plasma many illust.	free-free hydrogenic Gaunt factors,	well known
		CX from neutral beam deuterium to stripped impurities	Deduction of local T_i for D, He, Be, C & O at radial pts. Deduction of local v_{rot} for plasma at radial pts.	12. OVIII n = 10-9 fitted line shape many illust.	well known	
			Deduction of local n_i for D, He, Be, C & O at radial pts.	13. C & O density evol. in JET pulse many illust.	well known	
		Radiation by D in the neutral beams	σ & π D measurements to obtain internal B-field; full, 1/2 and 1/3 energy beam attenuation measure; excited D content of beam; Zeff measure	14. Dα emission from the beam - Stark cpts. (fig. 2.)	well known	
	VUV & EUV	Ionisation balance & radiated power	Dielectronic coefficients for complex Cr, Fe & Ni ions (fluorine- like to magnesium-like); consistent metastable treatment; possible extension to Al, Si, Mo, Kr	15. Dielectronic coefficient for Ni^{+17} (see refs.)	Very high Rydberg state energy level separations - dipole polarisabilities with ground & metastable cores; A-values	various incomplete!
		Line ratio diagnostics	Deuterium dilution from boron-like line ratios in Ni^{+23} & Kr^{+31}	16. KT4 spectrum of NiXXIV at 118A & 138A JET pulse #13868	Ground term M1 fine structure transition probabilities and $2s^22p\ ^2P_{1/2,3/2}$- $2s\,2p^2\ ^2D_{3/2,5/2}$ etc A-values.	reasonably known
	XUV & X-ray	Ionisation balance	Transport studies	17. Ni^{+27} & Ni^{+26} radial profiles		
		Ion temperature and plasma rotation	Plasma heating & electron-ion thermalisation	18. Ni^{+26} emission many illust.	Resonance, forbidden, intercomb. & satellite line parameters	reasonably known

In non-hydrogenic cases, the low l transition arrays diverge from the hydrogen-like transition energy and potentially cause a distorted n-n′ profile. Essential for analysing this are precise high Rydberg state energy levels and a sub-shell direct capture and redistribution model which gives the lj relative populations. The redistribution within an n-shell is strongly sensitive to the precise level separations. n-shells up to about 40 need to be included. A most useful presentation of this extensive energy level data is as polarisabilities. Such polarisabilities are useful in an other context to be described later. An associated set of problems and data requirements occur with partially stripped species and thermal hydrogen (see table 4).

Influx of BeI and CrI contrasted

Deduction of the flux of an impurity from a localised surface from observed column emissivities along a line of sight directed at the surface can be inferred if the theoretical quantity termed the 'ionisation per photon' or 'S/XB' ratio for each observed line is known. The inference is valid from any low ionisation stage of an element provided it has not significantly spread from its source before being ionised. Fluxes of both light and metallic impurities have been measured systematically from limiters, inner wall RF antenna screens etc. by this means. The calculation of the 'ionisation per photon' is interesting for a number of reasons. Firstly an inflowing ion generally has ground and metastable states whose populations are not necessarily strongly coupled in the highly ionising environment of the plasma edge. It requires therefore separate line observations, from each spin system at least, to evaluate the total flux. The choice of lines is also governed by the wish to use visible spectroscopy. For light impurities, the most suitable lines therefore have upper levels with n = 3 or 4 shell electrons and no dipole decay to the n = 2 shell so as to give favourable branching. A comprehensive collisional radiative model with uncoupled metastables is used to evaluate the populations and thence the ionisation per photon for the selected lines. Essential ingredients are non-dipole excitation cross-sections for $\Delta n > 0$ transitions, two-electron transition probabilities which tend to compete with the observed lines and corrections for cascading from higher quantum shells not included directly in the collisional radiative model. Further checks are necessary that charge transfer from the co-located neutral recycling hydrogen cloud is negligible. A valuable and consistent picture appears to have been established at JET for influx of CII, CIII, OII and OIII using these methods. (Behringer et al., 1989)

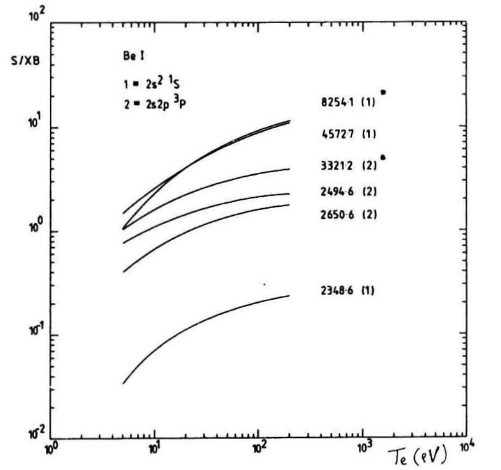

Fig. 4. S/XB ratios for BeI. * indicates preferred lines.

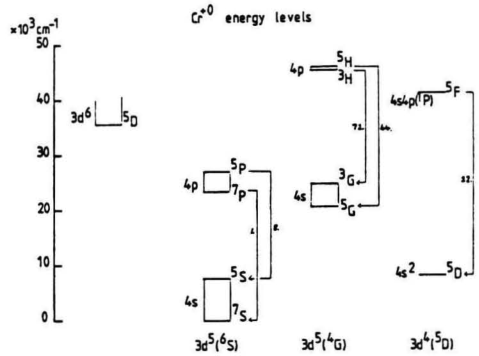

Fig. 5. Partial Grotrian diagram for CrI. (Behringer et al.,1989)

Consider however the situation for beryllium. This species has only been present in JET during 1989 and is under intense study. Clearly BeII with the 2s-2p resonance line at 3130A is the simplest ion for flux determination, but the wish to know more about release from the wall prompts study also of BeI. The atomic structure of BeI has been studied extensively. It displays strong configuration interaction, most notably the perturbation of the 2snd ^1D series by the $2p^2$ ^1D term. Doubly excited states of the form 2pnl (n > 2) generally lie in the continuum. The very small oscillator strengths for $2s^2$ ^1S - 2s3p ^1P and $2s^2$ ^1S - 2s4p ^1P are of note as is the large oscillator strength for $2s^2\,{}^1S$ - $2p3s\ {}^1P$ (a two electron transition with the upper state in the continuum. These complexities have created some anxiety and prompted us to select $2s2p\ {}^1P$ - $2s3s\ {}^1S$ at 8254A as a possible visible line for monitoring the singlet side. On the triplet side $2s2p\ {}^3P$ - $2s3s\ {}^3S$ at 3321A may just be usable. There does not appear to be a modern cross-section calculation available and so at present JET modelling uses fairly simple data. Preparatory studies on the UNITOR tokamak show a strong variation of metastable to ground population down to as low as 0.4 and with deviations of order 3 between theory and measurement for some lines. These are important issues for JET interpretation, but clearly the atomic data base must be made secure before proceeding much further (Forrest et al., 1989). Figure 4 shows S/XB ratios for BeI.

For the first and second ionisation stages of medium weight metals such as Cr, Fe and Ni the situation is rather different, partly because dipole allowed resonance transitions occur in the visible region, but mostly because of lack of detailed knowledge of energy level structure which allows association of lines with metastables (in practise, the best we can usually achieve is a linearly independent but non-orthogonal set of lines, so that a matrix equation must be solved for the metastable fluxes). A fortiori, good quality collision cross-section data is very limited. A detailed collisional radiative model cannot be supported. A partial Grotrian diagram for CrI is shown in figure 5. This indicates metastable states which might be important and spectrum lines which might be used to measure their fluxes. It is largely based on the work of Kurucz and Peytremann (1975). Measurements of metal influxes in JET are by far less complete than for light impurities. Furthermore a survey of limiter spectra based on different plasma pulses is unreliable because of the strongly varying metal coverage of the carbon tiles. Thus only the CrI 4254A (multiplet 1) line has been monitored routinely from the limiters and the quintet line 5208A (multiplet 8) has been measured on occasion. The chromium influxes for a strongly metal coated limiter case tend to indicate a small population for the ${}^5S$ state. In general no discrepancies have been encountered when asssuming the 4254A transition to be representative of the total neutral chromium flux. A capability for analysing metal influx is likely to become more important at JET in the light of possible divertor developments, as it is already in divertor machines such as ASDEX. For this reason we have a basic atomic physics study in progress on transition probabilities and collision cross-sections for CrI (Hibbert et al, 1988)

Line ratio diagnostics in JET

1 The powerful independent diagnostics for electron temperature and density profiles in the bulk plasma in JET have rendered line ratio methods for these quantities unnecessary. The dominant issues for spectroscopy are rather diffusion, impurity abundance and radiated power and so spectrum lines from different ionisation stages are compared with a view to infering ion transport. Large quantities of ionisation, recombination and line excitation data are used in the impurity transport codes and other global particle and power balance codes. The detailed interactive return to atomic physicists / spectroscopists from the use of their data has been rather low, partly because of calibration difficulties, partly because of the multiprocess dependence of most measurements, but mostly because of the complexity of the diffusion problem alone. The most direct information on ion diffusion is in fact obtained by transient injection of impurities either accidentally or intended by laser ablation. Such a system is in operation and a wide range of species have been used (Fe,Ni,Cu,Mo,Ag etc) (Magyar et al., 1988). Similarly rare gases have been introduced by gas puffing. The high plasma temperatures in JET have allowed spectra of very highly excited states to be acquired of interest for identification and precision wavelength studies as a by-product. Figure 6 shows such a molybdenum spectrum with the Li-like and Be-like resonance lines identified (Denne et al., 1989). Experience on ion diffusion and particularly the identification of zones where there is confidence that ionisation balance exists suggests that it would be worthwhile to invert the problem and try afresh

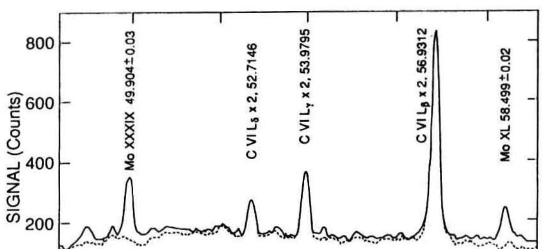

Fig. 6. Molybdenum spectrum following laser ablation.

to use line ratios from different ionisation stages to assess ionisation and recombination cross- sections. It is worth noting that dielectronic recombination of nickel ions around the Ne-like to Al-like stages is influenced by the finite plasma density in JET (factor of order 2) (Summers et al., 1987). Also it is desirable to adopt the more complete treatment of ionisation and recombination which handles metastables consistently in plasma modelling. High n-shell structure again plays a role (eg. dipole polarisabilities for metastable cores) Calibrated radial profiles from spectrometers such as KS2 (Table 1) with associated local densities and temperatures are very powerful for this. Also large statistical studies are possible exploiting the JET data base. For example, Ni^{+26} line ratios have been mapped and compared with theory for hundreds of samples over an electron temperature range from 3keV to 13 keV as illustrated in figure 7. (Zastrow et al., 1989)

The limited number of studies on single stage line ratios have tended to be primarily for cross-calibration or for simple checks on theoretical cross-sections. A possible exception may be highly ionised boron-like systems such as NiXXIV and KrXXXII where the forbidden line from the upper ground term fine structure level is observable and the competing collisional deexcitation is by ion impact. For NiXXIV in JET, it is more convenient to exploit the nearby lines at 118A and 138A (which arise from electron impact excitation from the ground and metastable to the $2s2p^2\ ^2D$ levels) rather than the forbidden line itself which occurs in a more remote wavelength region. At first impressions, this might be thought to be exploitable as an ion temperature indicator, but in practise, the ion tends to locate always at the same electron temperature. In circumstances when T_i and T_e are expected to be equal, the line ratio seems to be an indicator of 'dilution' (ie. the ratio of deuteron to electron density). Note this is most probably the dependence rather than Zeff because of the ion impact cross-sections' behaviour with energy. The preliminary study is promising and work is continuing.

FUTURE TRENDS

The active phase

Towards the end of JET, the machine will be prepared for deuterium/tritium operation in pursuit of one of its original goals, namely, plasma behaviour in the presence of significant heating by

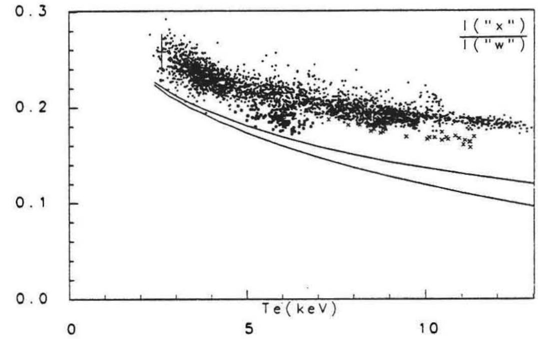

Fig. 7. Comparison of 'x' and 'w' line ratio for nickel. Solid curves show theoretical range.

fusion alpha particles. It will be necessary to measure these alpha particles, born at 3.5MeV and slowing by friction with electrons. It is possible that these cooling alpha particles might be detected spectroscopically following charge transfer from the neutral deuterium heating beams and the source function and parameters of the cooling distribution function determined. The HeII n = 4-3 spectral feature will have a finite width (of order 100A) because of the rapid fall of the charge exchange cross-section with relative speed above about 1.5 au. Figure 8 illustrates the form of the composite profile. Evidently the alpha particle feature must be detected against interfering species, which now include beryllium, the thermal helium feature and bremsstrahlung. The initial study for 80kev/amu beams suggests that detection will be possible at $Q_{D-T} = 1$.
The assessment of spectral features arising from non-thermal distributions is a problem at JET and is perhaps appropriately mentioned here. The

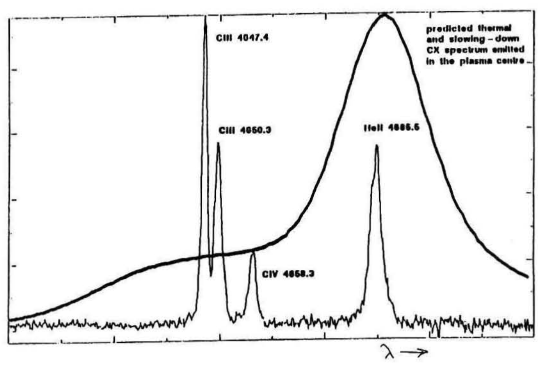

Fig. 8. Anticipated HeII (n = 4-3) profile (much amplified intensity) in the active phase.

alpha particle situation, in principal, is mimicked by ICRH heated helium minority species. A program is underway to seek evidence of such distorted features. Manifestly the whole cold and thermal feature emission must be isolated first with high confidence. High precision charge exchange data is essential, and JET is supported by AMOLF (Amsterdam) in this study.

Evidence for non-Maxwellian electron distributions, especially high energy tails in very high temperature fusion plasmas, is a perennial problem in which interest will increase again with the projected electron cyclotron resonance heating (ECRH). It must be admitted that there was some hope of obtaining clear evidence for a high energy electron tail from the Ni^{+26} KX1 study, but within the theoretical cross-section data errors this was not found. There is a further point, that kinematic relativistic corrections to electron impact rate coefficients is probably required.

Pumped divertors

It is certainly the case that any future large fusion machine will have a poloidal divertor designed to remove impurities and ash from the main plasma and seek to prevent (by efficient radiative cooling) sputtering of impurities and their migration back into the main plasma. It is possible that JET itself may be converted to a divertor machine at some stage. There is of course a substantial body of knowledge about divertors from the ASDEX tokamak, for example. It is within the relatively cool (10-150eV) divertor that the most pressing atomic and spectroscopic problems are expected. It is necessary to investigate the most suitable species for the target plates of the divertor and any other materials actively added to the divertor volume to achieve the required temperature and power shedding capability, and to assess by spectroscopic measurement whether the planned flows and inhibition of ion migration are produced. We anticipate making spectroscopic measurements on elements such as aluminium, silicon, nickel, copper, molybdenum and tungsten in the visible and uv/xuv. For example, molybdenum will be have to be studied as an inflowing species in stages Mo^{+0} and Mo^{+1} ,as a main radiating species in stages Mo^{+2} to Mo^{+11} and then on into high stages of ionisation to establish any link to the bulk plasma. It is anticipated that both spectral observation and transport modelling will require a pseudo-band structure approach base on shell groups of ions treated as a whole and evolving from one to another. We are planning on this basis at the present time using rudimentary atomic and spectroscopic data. Figure 9 shows the spectral locations of the transition arrays for some of the relevant molybdenum ions.

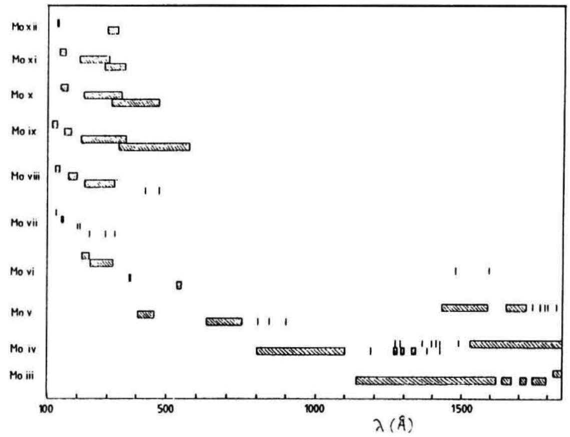

Fig. 9. Wavelength positions of transition arrays of MoIII - MoXII.

Surface interactions

It is at the bounding surface of the plasma that the greatest deficit of atomic/molecular/spectroscopic understanding appears to lie, at least in our awareness of it at JET. The release of impurites from surfaces clearly has a chemical dimension but as yet we have made no studies of molecular species and their catabolism in JET. Figure 10 identifies the CH band in a JET spectrum to demonstrate that the molecules do exist (Behringer et al., 1986). We wish to model molecular break-up and emission in the same manner as the collisional-radiative modelling for atomic ions in an effort to understand impurity release and the state and speeds of the inflowing atoms. We anticipate significant development of application of molecular spectroscopy and reaction kinetics to fusion plasma boundaries.

Energetic highly ionised ions striking surfaces are of course very effective also in releasing secondary electrons. There is at the present time no consistent model of the scrape-off-layer and the surface sheaths which incorporates an atomic description of this release, yet independent beam/surface experiments are successfully showing these effects and establishing a spectroscopic signature of the emission associated with the cascade/Auger neutralising of the impacting ion.

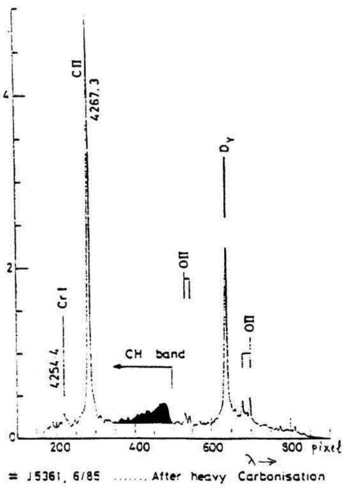

Fig.10. CH band in a JET spectrum

CONCLUSION

This paper has identified some main areas of activity in atomic physics and spectroscopy in JET and has speculated on where future activities may occur. It has been pointed out that there is an extensive and still developing spectroscopic capability on JET reinforced by a large diagnosic and computational infra-structure. It is hoped that the intriguing behaviour of the plasma will prove an incentive to atomic physicists and spectroscopists to support and become involved in some of these studies.

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