CLM-P633

UKAEA

Preprint

ACCURATE MEASUREMENTS OF 1s2s ^3S-1s2p ^3P TRANSITION WAVELENGTHS OF HELIUM-LIKE IONS IN TOKAMAK PLASMAS

M. F. STAMP
I. A. ARMOUR
N. J. PEACOCK
J. D. SILVER

CULHAM LABORATORY
Abingdon Oxfordshire

1981

CLM-P 633

ACCURATE MEASUREMENTS OF 1s2s ^{3}S-1s2p ^{3}P TRANSITION WAVELENGTHS OF HELIUM-LIKE IONS IN TOKAMAK PLASMAS

M F Stamp[*+] I A Armour[*o] N J Peacock[+]

and J D Silver[*]

Culham Laboratory, Abingdon, Oxon. OX14 3DB, U.K.

(Euratom/UKAEA Fusion Association)

ABSTRACT

We report new measurements of the wavelengths of the 1s2s ^{3}S-1s2p ^{3}P transitions in the helium-like ions of oxygen and fluorine, using a Tokamak as a light source. Results are compared with theory and it is shown that our results, and most of the experimental results of other groups for these transition wavelengths in helium-like ions with $Z < 10$, may be brought into agreement with theoretical values if a small semi-empirical correction is applied.

(To be submitted to J. Phys. B, Atom. Molec. Phys.)

* University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU.
Nuclear Physics Laboratory, Keble Road, Oxford OX1 3RH.

+ Culham Laboratory, Abingdon, Oxfordshire OX14 3DB.

o Central Electricity Generating Board, Marchwood Engineering Laboratories, Southampton SO4 4ZB.

December 1980

INTRODUCTION

The two-electron atom is an excellent system for testing theories of atomic structure, so that a great deal of experimental work has been done on its properties. An area of this research where developments in technique have recently led to new information being obtained is the accurate measurement of the wavelengths of $1sns\,^3S$-$1snp\,^3P$ transitions for high Z helium-like ions. Following some early suggestions concerning the influence of quantum electrodynamic effects in helium and the helium-like ions (see Edlen 1952 for references) the particular sensitivity of the ^3S-^3P transitions in high Z helium-like ions to relativistic and quantum electrodynamic effects has been more recently stressed by Accad et al (1971), Kastner (1972) and Gould and Marrus (1976). An indication of the sensitivity to Q.E.D. effects may be judged from Figure 1, which shows the ratio of the one electron Lamb shift contribution to the total energy difference for the particular transition $1s2s\ ^3S_1$-$1s2p\ ^3P_0$ plotted as a function of Z. The Lamb shift contribution is taken from the values of Mohr (1976) and the total $1s2s\ ^3S$-$1s2p\ ^3P_0$ energies are taken from Ermolæv and Jones (1974), whose calculations of energies of helium-like ions are the most complete currently available in the literature for all Z, though less complete calculations are available (Davis and Marrus, (1977), Berry, DeSerio and Livingston, 1980). A number of measurements have recently been made of the wavelengths of the $1s2s\ ^3S$-$1s2p\ ^3P$ transitions of helium-like ions in the range Z=14 to Z=26 (Davis and Marrus 1977, Berry et al 1978, O'Brien et al 1979, Armour et al 1979, Livingston et al 1980): all these measurements have used the same technique as Davis and Marrus, who employed a scanning vacuum monochromator to study transitions from the $1s2p\ ^3P$ states in the helium-like ions of argon excited in a fast ion beam source, using the method of beam foil spectroscopy. The typical experimental errors quoted in the above recent measurements correspond, when reduced to a fractional error $\delta\lambda/\lambda$, to $>\pm 10^{-4}$, whilst the best wavelength measurements which have been made in the spectral region of the ^3S-^3P transitions have a $\delta\lambda/\lambda$ error of $\sim 10^{-6}$ (Kaufman and Edlen 1974). The dominant sources of error in the beam foil spectra are systematic, and may be attributed to a combination of factors. The most important factor is the high beam velocity required ($v/c \sim 10^{-1} - 10^{-2}$) to produce an adequate yield of excited helium-like states. This gives rise to large Doppler effects, which then produce broadening and shifts of the observed spectra. Although techniques exist for the reduction of this broadening (Jelley, Silver and Armour, 1977), these give rise to problems of calibration, and accurately known calibration lines are often not emitted by the beam foil source. Another contribution to the errors comes from insufficiently precise instrumentation.

The theoretical interest in the $^3S-^3P$ transitions, coupled with the errors associated with other methods used to date, suggests the use of Tokamak plasmas as a source of excited helium-like ions for accurate spectroscopy, and in this paper we describe experiments to measure the 1s2s ^3S-1s2p ^3P transition wavelengths of helium-like ions of oxygen and fluorine. We present a comparison between theory and experiment for these transition wavelengths, and comment on the application of this technique to higher Z helium-like ions.

EXPERIMENT

The experimental set up is shown in figure 2. The spectrum of radiation in the vacuum UV region from the DITE (Divertor Injection Tokamak Experiment) tokamak at the Culham laboratory was investigated with a Rank Precision (Hilger and Watts) type E766 1 metre, normal incidence, concave grating spectrometer equipped with a 1200 l/mm Pt coated grating, using photographic recording on Kodak Pathe SC-5 film. The helium-like ions of oxygen and fluorine impurities were predominantly produced in regions of the plasma having electron temperatures of 400-700 eV. At this temperature, and for a transition wavelength of 150nm, the Doppler broadened fwhm linewidths are ≈ 0.06 nm. Impurity ions in the plasma, notably carbon, oxygen, nitrogen, silicon and titanium, emit radiation in the spectral region around the 1s2s ^3S-1s2p ^3P transitions of O and F. These transitions are in comparatively low charge states: this has the dual advantage that their wavelengths are often well known ($\delta\lambda < \pm.0001$nm) from previous spectroscopic studies (references for calibration wavelengths used are given in table 2) and that since they arise from lower charge states, they are excited in cooler parts of the plasma so that their half widths are lower (≈0.03nm fwhm). Relative mass motions of different temperature regions of the plasma could introduce systematic errors, but they were found to be negligible for the DITE tokamak under the operating conditions in which spectra were recorded, as described below.

Helium-like oxygen spectra were recorded in 3 or 4 tokamak discharges ($n_e \sim 1\text{-}4 \times 10^{13}$ cm^{-3}, $I_p \sim 50\text{-}100$ kA) with a spectrometer entrance slit width of 50μm, corresponding to an instrumental FWHM of .04nm on the film. The 1s2s $^3S_1$-1s2p $^3P_2$ transition was correctly exposed in 3 or 4 tokamak discharges with a 20μm entrance slit, though concomitantly, some of the weaker calibration lines failed to appear on the film.

Fluorine is a much weaker impurity than oxygen so comparable fluorine spectra were recorded with 10-15 tokamak discharges ($n_e = 1\text{-}5 \times 10^{13} cm^{-3}$, I_p = 100-200 kA and up to 1 MW of neutral beam injection). Even with this exposure the $^3P_1$ transition was too weak to be observed.

The positions of the spectral lines on the films were measured using an Abbe comparator (model B), with a measuring accuracy of ±0.5μm. A calibration curve was found for each film, where a linear relation was assumed between wavelength and distance along the film. The residuals between the reference lines and their wavelengths derived from the linear calibration (see fig.3a, 3b) were then used to calculate corrections to the simple linear fit. Table 1 shows the mean oxygen and fluorine helium-like wavelengths from several films. Table 2 gives the assumed wavelengths of the calibration lines, and the experimental values derived by the same procedure as for the helium-like lines.

The errors quoted are a combination of errors in the measurements of line centres (typically ±5μm corresponding to ±0.004 nm) and errors from the calibration curve fitting procedure. Line asymmetries due to hyperfine splitting in the fluorine spectra contribute to their quoted error. Doppler shifts between ions in different parts of the plasma are not evident from table 2 or figs. 3a and 3B, but there is additional evidence that they are negligible. The UV spectrum from the DITE tokamak was examined from 200-450nm (with a best resolution of ±0.006nm) when the tokamak plasma current was run both anti-clockwise (as in normal use) and clockwise and with and without tangential beam injection, and no evidence was found for relative Doppler shifts (due to toroidal ion motion) in ions ranging from O II and Ti II to O VI and Ti XVII. In the present work the spectrometers viewed the plasma tangentially (i.e. in the toroidal direction); radial viewing would have been preferable since the beam induced toroidal rotation of the plasma in some tokamak operation conditions can be as much as two orders of magnitude higher than the radial ion velocity, Peacock et al (1978).

DISCUSSION

A comparison between previous experimentally observed $^3S-^3P$ transition wavelengths (see table 3) for the helium-like ions with Z = 2 - 10 and the theoretical values of Ermolæv and Jones (1974) and Berry, De Serio and Livingston (1980) is shown in Figs. 4a, b and c, where log $(E_{expt} - E_{th})$ is plotted against log Z. It is interesting to note that for both theoretical values there is a systematic difference between the theory and experiment. This difference scales approximately as Z^n. The actual value of n depends weakly on the range of Z considered, but is approximately 3 for the calculations of Ermolæv and Jones (1974) and somewhat less than 3 for the calculations of Berry et al (1980). Two exceptions to this trend are the 1s2s $^3S_1$ - 1s2p ^3P_o transitions of N VI and F VIII, which suggests an underestimate of the error in these measurements.

Energies which scale approximately as Z^3 include two-electron fine structure and radiative effects. Two-electron fine structure has been included in both calculations by using Breit-Pauli terms in perturbation theory, and should give adequate accuracy for the Z^3 terms. However, both the calculations of Ermolæv and Jones (1974), and of Berry et al (1980) have neglected some two-electron radiative effects. It has been pointed out by Brodsky and Mohr (1978) that the dominant contributions to the Lamb shift in two-electron ions arising from electron-electron interactions will scale approximately as (I/Z) x (one-electron Lamb shift). These contributions are of a similar magnitude to the discrepancies between theory and experiment, as may be seen from Figs. 4a, b and c, where log (I/Z x (one-electron Lamb shift)) is also plotted as a function of Z.

Detailed consideration of both calculations shows that Ermolæv and Jones (1974) have evaluated the two-electron Lamb shift as given by Kabir and Salpeter (1957) by using a hydrogenic approximation for the low momentum part of the self energy term both for the density at the nucleus and for the Bethe logarithm. These approximations are discussed by Armour (1980).

More accurate calculations of the electron density at the nucleus change the $2^3S - 2^3P$ splitting by $0.026\ Z^3\ cm^{-1}$ but in the wrong direction. A more accurate Bethe logarithm also gives rise to a term scaling as Z^3. Berry et al (1980) used a purely hydrogenic Lamb shift so their calculations will have the above discrepancies as well as a Z^3 term arising from the use of a hydrogenic electron density at the nucleus in the other parts of the Lamb shift.

The smooth trends in the difference curves of fig. 4 suggest that a semi-empirical procedure may be used to test the present tokamak results. To do this, the differences between the experimental and the theoretical values of Ermolaev and Jones for the helium-like 1s2s $^3S_1$-1s2p $^3P_{0,1,2}$ transitions were fitted to functions of the form $E_{expt}-E_{th} = \alpha Z^3 + \varepsilon$, using a least squares fit. The fitted values of α and ε can then be used to determine a "best fit" transition energy for any given Z (in practice, ε is negligible compared to the experimental errors for $Z>4$). Table 4 compares the "best fit" transition energies calculated in this way with the tokamak measurements, and it can be seen that the agreement is reasonable; similar results are found if a similar procedure is adopted with the theoretical values of Berry et al.

The discrepancy which exists between theory and experiment indicates that there is a need for better calculations, although the semi-empirical approach may be applied to obtain better values of transition wavelengths. It should also be possible to operate stable tokamak discharges with up to several percent impurity concentrations, the impurities being introduced by laser evaporation of i.e. metal-film-glass interfaces (see Cohen et al 1975). This would facilitate a systematic study of transitions such as those reported here over a wide range of helium-like ions, including ions of higher nuclear charge, Z, where a more critical test of theory may be possible.

ACKNOWLEDGEMENTS

The authors wish to acknowledge very helpful discussions with S J Fielding, H Gordon, H A Gould, M G Hobby, H Klein, P J Mohr, E G Myers and E Träbert. The experimental assistance of the DITE group and A H Jones from the diagnostics group at the Culham laboratory has been an essential ingredient to this study.

REFERENCES

Accad Y, Pekeris C L and Schiff B, 1971 Phys.Rev. A4 516

Armour I A, Myers E G, Silver J D and Träbert E, 1979 Phys.Lett 75A 45

Armour I A, 1980 D. Phil Thesis, University of Oxford, Unpublished

Berry H G, De Serio R and Livingston A E, 1978 Phys.Rev.Lett. 41 1652

Berry H G, De Serio R and Livingston A E, 1980 Phys.Rev. A22 998

Brodsky S J and Mohr P J, 1978 Structure and Collisions of Ions and Atoms, ed. I A Sellin (Springer Berlin) 3

Cohen S A, Cecchi J L and Marmar E S, 1975 Phys.Rev.Lett. 35 1507

Davis W A and Marrus R, 1977 Phys.Rev. A15 1963

Edlen B, 1952 Ark for Fys 4 441

Ermolaev A M and Jones M, 1974 J.Phys. B7 199

Gould H A and Marrus R, 1976 Beam Foil Spectroscopy Vol.1 ed. I A Sellin and D J Pegg (Plenum Press) 305

Jelley N A, Silver J D and Armour I A, 1977 J.Phys. B9 1

Kabir P K and Salpeter E E, 1957 Phys.Rev. 108 1256

Kastner S O, 1972 Phys.Rev. A6 570

Kaufman V and Edlen B, 1974 J.Phys.Chem.Ref.Data 3 825

Livingston A E, Hinterlong S J, Poirier J A, De Serio R and Berry H G, 1980 J.Phys. B13 L139

Mohr P J, 1976 Beam Foil Spectroscopy Vol. 1 ed. I A Sellin and D J Pegg (Plenum Press) 89

O'Brien R, Silver J D, Jelley N A, Bashkin S, Träbert E and Heckmann P H, 1979 J.Phys. B12 L41

Peacock N J, Hughes M H, Summers H P, Hobby M G, Mansfield M W D and Fielding S J, "Plasma Physics and Controlled Fusion Research 1978" Vol. 1 303-314. Publ. IAEA, Vienna, 1979

TABLE 1

Helium-like $2\ ^3S-2\ ^3P$ transition wavelengths for oxygen and fluorine in DITE (Divertor Injection Tokamak Experiment). The oxygen values are the mean of four measurements. The fluorine $^3S_1-^3P_2$ value is the mean of four measurements, while the other is from a single observation.

	OXYGEN	FLUORINE
$2\ ^3S_1 - 2\ ^3P_2$	162.364 (±0.008)	141.431 (±0.006)
$2\ ^3S_1 - 2\ ^3P_1$	163.836 (±0.005)	-
$2\ ^3S_1 - 2\ ^3P_0$	163.990 (±0.005)	143.70 (±0.01)

TABLE 2

List of calibration lines with their experimentally determined wavelengths from DITE.

OIII, IV, V wavelengths at <800 were observed once only and in second order.

Ion	Assumed Wavelength (nm)	Ref.	Experimental Wavelength (nm)	
C II	133.4532	a	133.454	0.003
C II	133.5708	a	133.571	0.003
O IV	133.8603	b	133.865	0.006
O IV	134.3507	b	134.350	0.006
O V	137.1292	c	137.129	0.004
Si IV	149.3755	c	149.375	0.003
Si IV	140.2770	c	140.278	0.003
O III	70.2896	b	70.289	0.003
O III	70.3850	b	70.386	0.003
Ti III	142.2408	d	142.244	0.006
Ti III	145.5195	d	145.518	0.003
Ti III	149.8695	d	149.869	0.003
O V	75.8677	b	75.868	0.003
O V	75.9440	b	75.945	0.003
O V	76.1130	b	76.112	0.003
O V	76.2001	b	76.201	0.003
C IV	154.8202	e	154.820	0.008
C IV	155.0777	c	155.075	0.008
C I	156.0682	a	156.066	0.003
C I	156.1438	a	156.143	0.004
O IV	78.7710	b	78.773	0.003
C I	165.6267	a	165.629	0.006
C I	165.7008	a	165.700	0.003
N IV	171.8551	b	171.859	0.006
C II	176.0395	a	176.038	0.006

a) Kaufman V and Edlen B, 1974 J. Phys.Chem.Ref.Data 3 825

b) Fawcett B C, 1975 Atomic Data and Nuclear Data Tables 16 2

c) Kelly R L and Palumbo J, 1973 Atomic and Ionic Emission Lines below 2000A, NRL Report 7599

d) Corliss C and Sugar J, 1979 J. Phys.Chem.Ref.Data 8 1

e) Edlén B, 1979 Physica Scripta 19 255

TABLE 3

(Previously published data, for n=2 $^3P_{2,1,0}$ levels of He-like ions, used to compute difference shown between theory and experiment in figures 4 a,b,c.)

ION	Z	ION SOURCE	$^3P_2$ (cm^{-1})	$^3P_1$ (cm^{-1})	^3P_o (cm^{-1})	REFERENCE
Li II	3	Ion beam (Laser fluorescence)	18228.198(.001)	18226.108(.001)	18231.303(.001)	Holt et al
Be III	4	Hollow spark Sliding spark	26867.9(.2)	26853.1(.2)	26867.5(.7)	Löfstrand Eidelsberg
B IV	5	Vacuum spark	35429.5(.6)	35377.2(.6)	35393.2(.6)	Edlén
C V	6	Vacuum spark	44021.6(1.0)	43886.1(1.0)	43899.0(1.0)	Edlén and Löfstrand
N VI	7	θ- Pinch	52719.5(.6)	52429.0(.6)	52413.9(1.4)	Baker
O VII	8	θ-Pinch	61590.4(3.0)	61038.9(3.0)	60980.4(3.0)	Engelhardt and Sommer
F VIII	9	θ-Pinch	70700.4(3.0)	69743.8(3.0)	69586.0(3.0)	Engelhardt and Sommer
Ne IX	10	θ-Pinch	80120.5(1.3)	78566.3(2.4)	78266.9(2.4)	Engelhardt and Sommer

Holt R A, Rosner S D, Gaily T D and Adam A G, 1980 Phys. Rev. A22 1563
Lofstrand B, 1973 Physica Scripta 8 57
Eidelsberg M, 1972 J.Phys. B5 1031
Edlen B, 1934 Nova Acta Reg. Soc. Sci. Ups. (IV) 9 No 6
Edlen B and Löfstrand B, 1970 J.Phys. B3 1380
Baker S C, 1973 J.Phys. B6 709
Engelhardt W and Sommer J, 1971 Ap.J. 167 201

TABLE 4

Comparison of tokamak results with the theory of Ermolaev and Jones (1974) plus the semi-empirical correction (see text).

	OXYGEN		FLUORINE	
	Theory with correction	This Experiment	Theory with correction	This Experiment
	cm^{-1}	cm^{-1}	cm^{-1}	cm^{-1}
$^3S_1 - {}^3P_2$	61588.7	61590.0 (±3)	70699.7	70705.8 (±3)
$^3P_1$	61038.3	61036.6 (±1.8)	69744.4	-
$^3P_0$	60979.6	60979.3 (±1.8)	69593.4	69589.4 (±5)

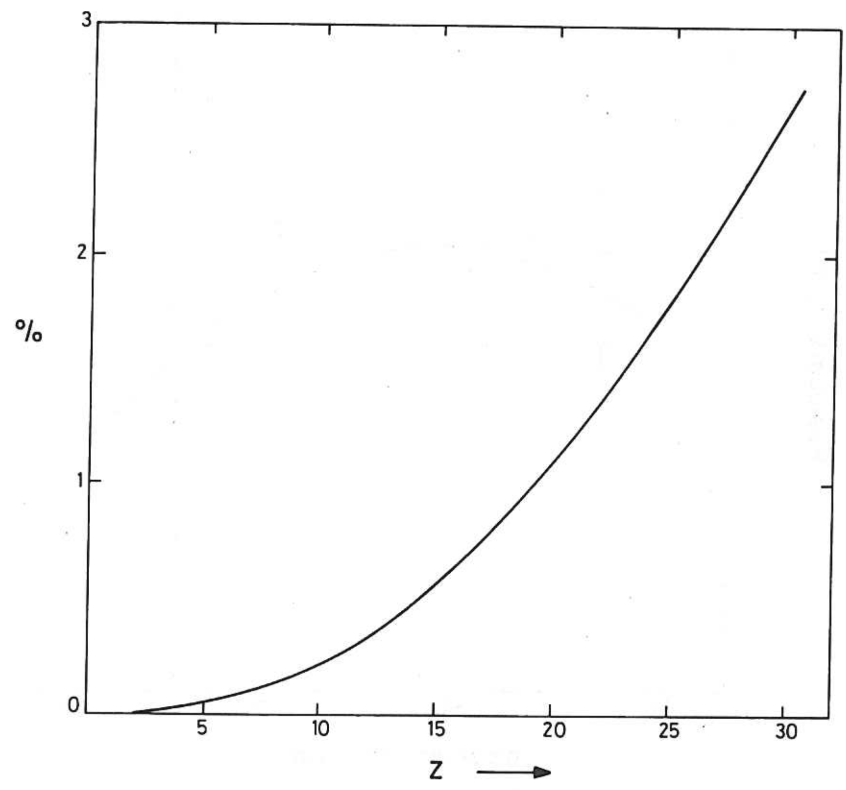


Fig.1 Variation with nuclear charge Z of Lamb shift contribution to the 1s2s $^3S_1 - 1s2p\ ^3P_0$ transition in helium-like ions.

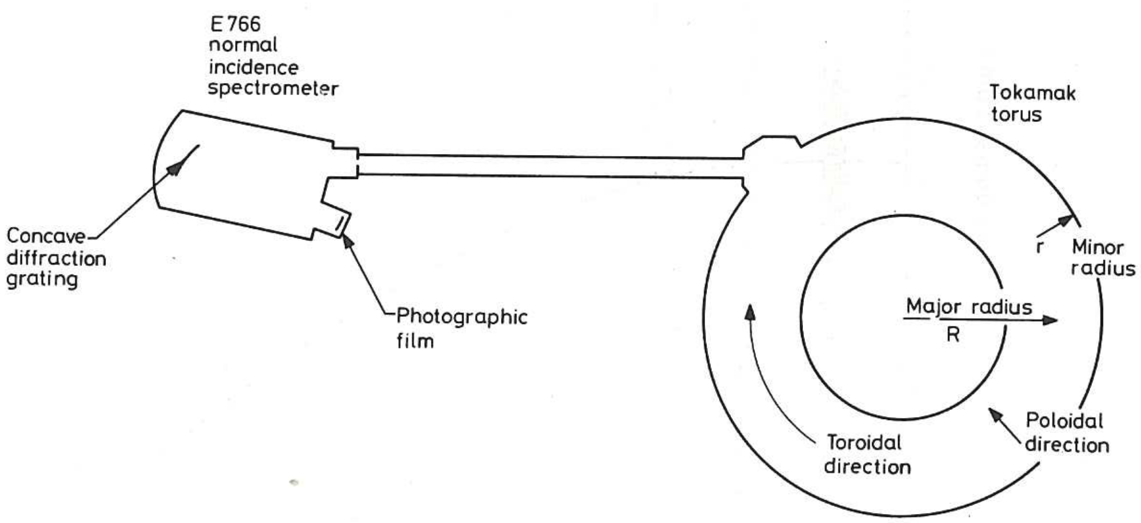
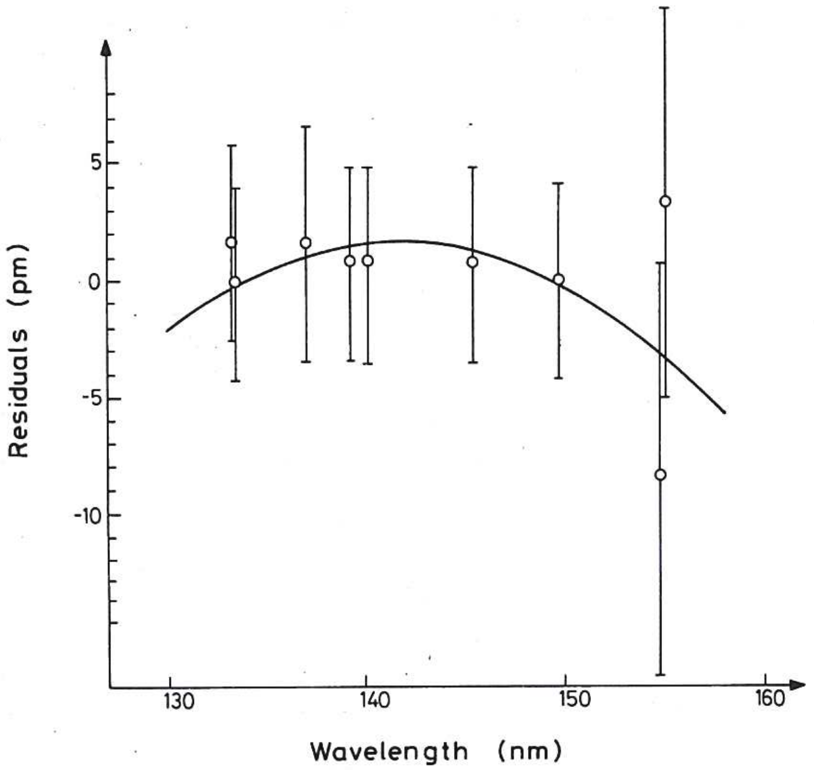
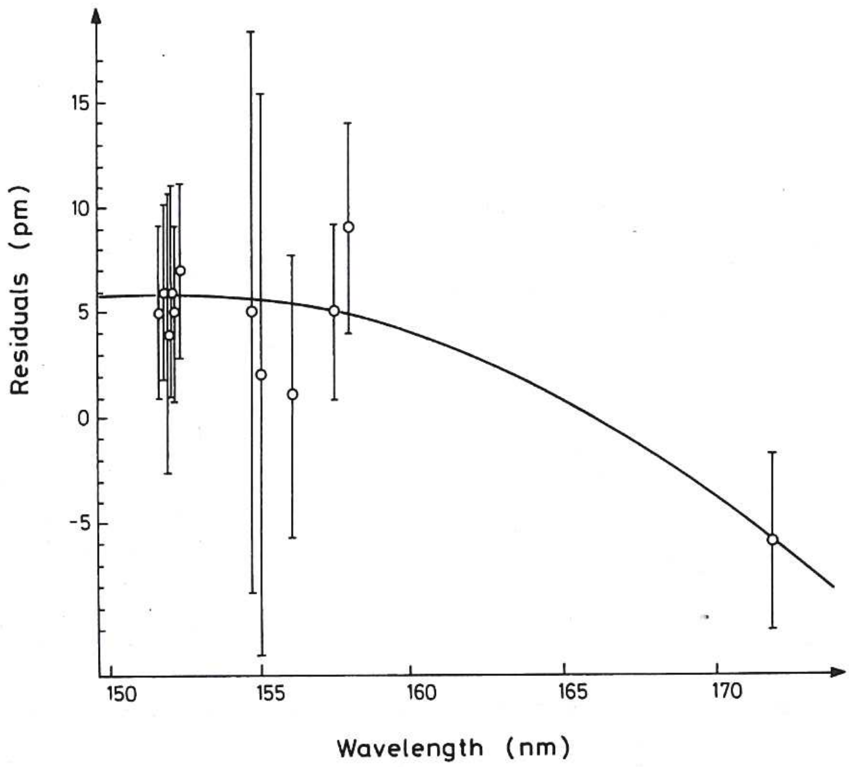


Fig.2 Experimental set up to observe vacuum ultraviolet spectra from the DITE tokamak.



(a)



(b)

Fig.3 Deviations from calibration curves for two typical photographic plates.

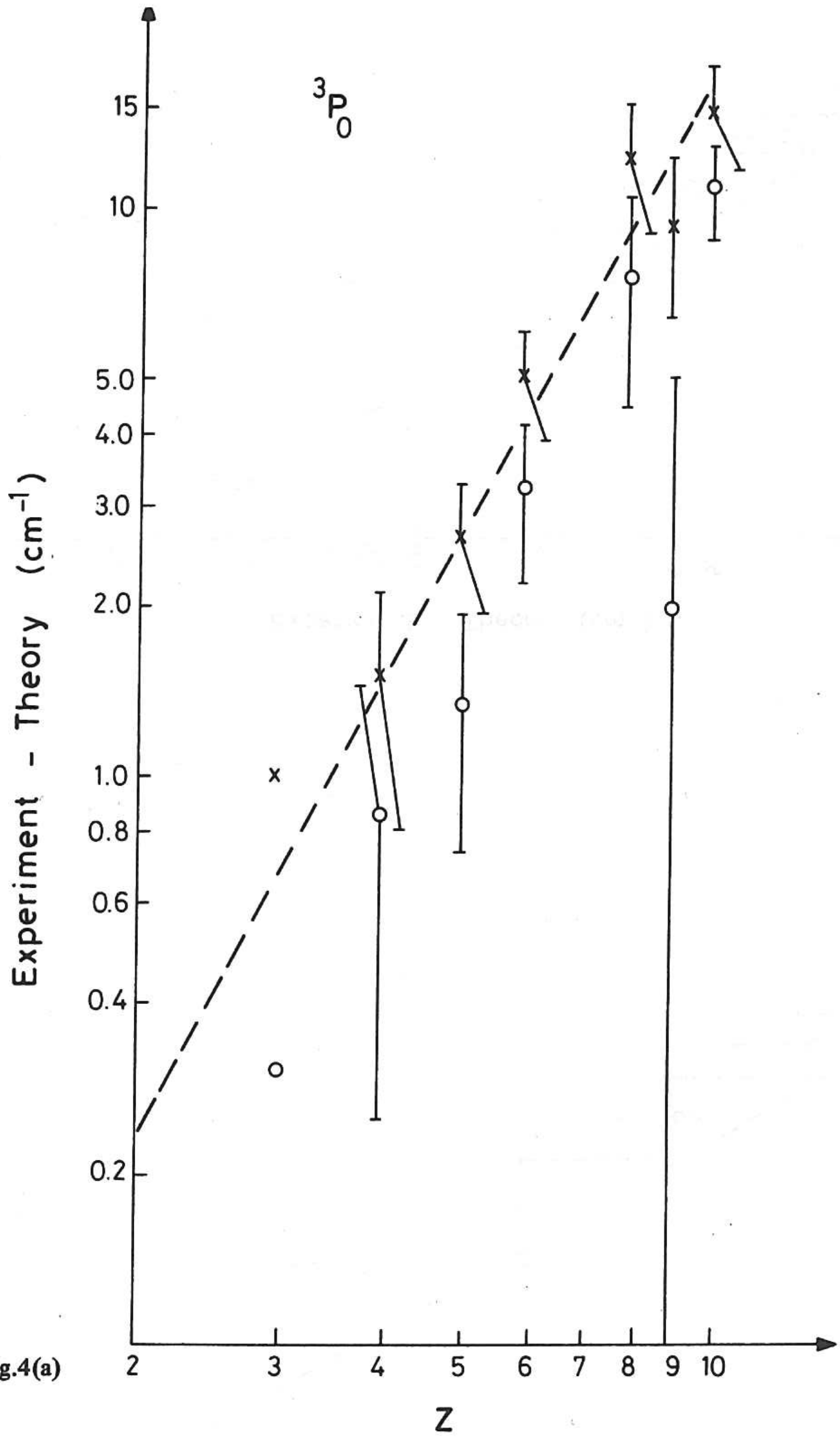


Fig.4(a)

Fig.4 Variation with nuclear charge Z of the difference between experimental Table 3 and theoretical results for the transitions 1s2s ^3S–1s2p $^3P_0$ (a) – 1s2p $^3P_1$ (b) and – 1s2p $^3P_2$ (c) in helium-like ions. The figures are plotted on log-log scales; also shown is the quantity 1/Z x 2 $^2S_{1/2}$–2 $^2P_{1/2}$ Lamb shift of the hydrogenic ion of corresponding Z. The theoretical results of Berry (1980) correspond to the crosses, and those of Ermolaev and Jones (1974) to the open circles.

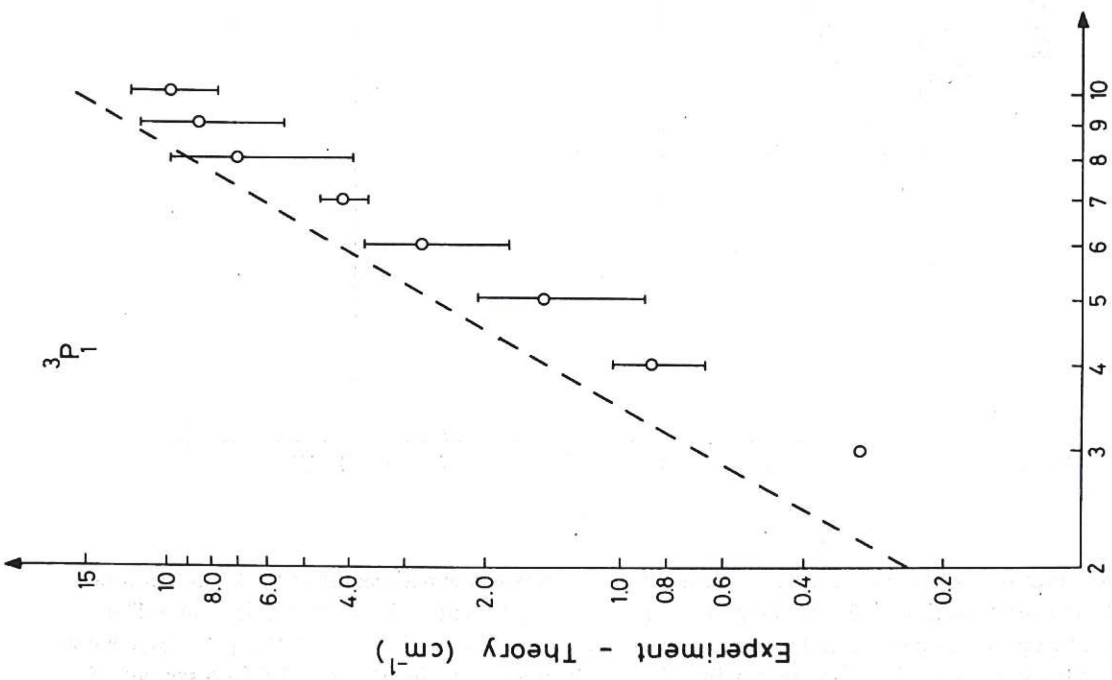


Fig.4(b)

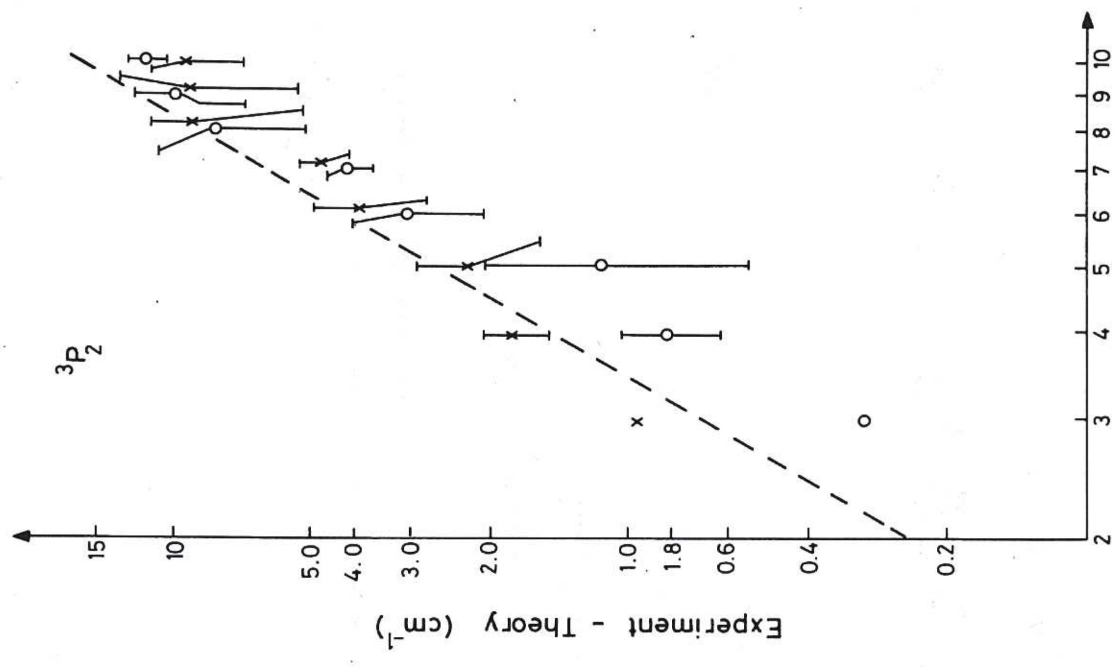


Fig.4(c)

CLM-P633