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GRAZING INCIDENCE SPECTRA OF HIGHLY-IONIZED ATOMS FROM LABORATORY PLASMAS

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A B S T R A C T

Radiation from high temperature plasmas produced in the ZETA and Thetatron discharges has been studied down to the soft X-ray region using grazing incidence spectrographs. Two forms of instrument have been used; one designed for laboratory studies, and the other for solar observation from rockets. Both use 600 line/mm ruled gratings at grazing angles between 1° and 4°. The resonance line of NeIX at 13.44 Å is the shortest wavelength so far observed. New spectra are reported from NeVII, NeVIII, AIX, AX, AXI, AXII, and XeIX.

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CONTENTS

1. INTRODUCTION

Previous ultra-violet studies of high temperature plasmas have been carried out mainly in the region down to 200 Å. Measurements in this region have been made at Culham by Butt et al, (1958), Gabriel, Niblett and Peacock (1962), and Jones and Wilson (1962). At shorter wavelengths, measurements have been made at Los Alamos by Jahoda, Ribe, Sawyer and Stratton (1961) using a crystal X-ray spectrometer, and extending up to about 25 Å. The development of grazing incidence instrumentation at Culham has enabled this gap to be closed and measurements are now being made well into the normal crystal spectrometer region, using these techniques.

Previous work on the study of highly-ionized spectra in the range above 50 eV photon energy has chiefly involved the use of vacuum spark sources. The early work of Edlén (1934) has been followed by many further studies notably by the Swedish workers. A study of the Atomic Energy Levels (Moore, 1949) indicates a fairly comprehensive classification of many of the elements. There is however a notable lack of information on highly-ionized ions of inert gases. This is due to the difficulty of introducing gases into the spark sources. The existence of gas discharges operating at high temperatures has now overcome this problem as is shown by the work of Fawcett, Jones and Wilson (1961) and Bockasten, Hallin and Hughes (1963). The present work provides measurements up to nearly kilovolt photon energies by studying plasmas in the grazing incidence region. This has been aimed at improving the general understanding of short wavelength radiation from plasmas, as well as identifying new lines in the inert gas spectra. Some of the early measurements using ZETA as a source have been reported briefly (Fawcett, Gabriel, Griffin, Jones and Wilson, 1963). Measurements have now been made also using two Thetatron devices, and several new lines of Neon and Argon have been observed and identified.

2. SPECTROGRAPHS

Two spectrographs have been used in this work. The first is a rocket instrument designed to study the solar spectrum from above the atmosphere. It is a small photographic instrument using a Bausch and Lomb 1 metre 600 line/mm blazed replica grating. It is capable of operation at grazing angles between 1° and 4° and will record from 550 Å down to a mechanical limit of around 12 Å, depending on the grazing angle used. This instrument has been fitted with a vacuum tank and used to record spectra from ZETA. An aluminium filter has been used for some of the measurements to improve the discrimination against scattered radiation of longer wavelengths.

The second instrument used is a larger 2 metre spectrograph designed for laboratory use. A detailed description of this instrument is being given elsewhere (Gabriel, Swain and Waller, 1964). It uses a 600 line/mm grating at 1°, 2° or 4° grazing angle and has its Rowland Circle orientated in a vertical plane. Bausch and Lomb gratings, both blazed replicas and faintly ruled originals, have been used.

3. PLASMA SOURCES

Three different plasma sources have been used in this work.

3.1 ZETA (Butt et al, 1958). The discharge was operated in deuterium with a filling pressure of 0.5 mTorr, often containing a few per cent addition of some other gas. Gas currents of up to 630 kA were used together with axial magnetic fields of up to 1040 gauss. The rocket spectrograph was used on this device and spectra were recorded on S.W.R. film, both with and without an aluminium filter and over a range of gas currents. The shortest wavelength observed was the Lyman β line of Oxygen VIII at 16.0 Å. It is not known whether the source or grating is the limiting factor in this case. Fig.1(a) shows a spectrum from a discharge containing 5% of Argon. It was recorded at 1° grazing angle.

3.2 Small Thetatron. In this device a stored energy of 3 kJ at 30 kV is discharged into a single turn coil of 5 cm diameter around a quartz tube containing about 100 mTorr of deuterium. By adding increasing quantities of from 1% to 20% of other gases it was found possible to photograph their spectra. The larger quantities cooled the discharge and thus helped to separate the degrees of ionization of the spectra. This discharge was viewed axially using the 2 metre spectrograph at 2° grazing angle. The line of shortest wavelength obtainable was the Oxygen VII transition $1^{1}S - 2^{1}P^{o}$ at 21.6 Å, the source being the limitation in this case.

3.3 MAGGI I Thetatron (Gabriel, Niblett and Peacock, 1963). This is similar to the above source but has a larger stored energy of 30 kJ at 25 kV. The discharge tube is made from recrystallized alumina, and the 2 metre spectrograph was used for photographing the spectra. This device produced the highest energy spectra of the three, and the line of shortest wavelength recorded was the NeIX transition $1^{1}S - 2^{1}P^{o}$ at 13.44 Å. With the instrument working at 2° grazing angle, this limit might be due to grating cut-off. Fig.1(b) shows the short wavelength end of such a spectrum, from a discharge containing 5% Neon. It is obtained from 30 superposed discharges and shows, in addition to the two NeIX lines at 13.44 Å and 13.55 Å, lines of oxygen, nitrogen and carbon.

4. INTERPRETATION OF SPECTRA

Spectra obtained from ZETA had some essential differences from those of the Thetatrons. Both types displayed the H-like and He-like lines of the common impurities, carbon, nitrogen and oxygen, in the region 16 Å to 40 Å, as is shown clearly in Fig.1(b). However, whereas the Thetatron shows a strong spectrum from lower degrees of ionization at longer wavelengths, these are comparatively weak in the ZETA spectrum. This might be due to the relative absence from ZETA of the outer layers of cooler plasma, which are very prominent in the Thetatrons, or also to the existence in the Thetatron discharges of later half-cycles of current, giving cooler and contaminated plasmas. The other prominant feature of the ZETA spectrum is completely absent from the Thetatron. This is the intense system of lines from 170 Å - 212 Å which were reported in the earlier publication (Fawcett et al, 1963). Work on the identification of these is proceeding and will form the subject of a separate publication. It can now be confirmed, however, that the element responsible for the stronger lines is iron, presumably from the walls of the discharge vessel.

The spectrograms recorded in these experiments were measured with a travelling microscope. Using known calibration standards, chiefly of oxygen lines, the other wavelengths were then calculated. This was carried out on the IBM 7030 computer using a polynomial interpolation programme. The accuracies obtained varied from 0.03 Å to 0.07 Å, depending on the proximity of good standards. Where lines could be measured in higher orders, these figures were correspondingly improved.

Most of the analysis of new lines has been confined to Neon and Argon spectra, although a few new lines of Xenon have been identified. Ions up to Neon IX and Argon XII have been observed. The three plasmas used produced differing degrees of ionization of these gases. These were, in descending order; the MAGGI I Thetatron, ZETA and the small Thetatron. In addition some variation was possible in each by studying the discharges at different energy inputs and heavy gas concentrations. By these means it was possible in many cases to separate lines due to different degrees of ionization. The classification was carried out by comparing measured wavelengths with those calculated by iso-electronic extrapolation and interpolation. At first these calculations were based upon the well known formulae for term values (White, 1934, p.331). In later work it was found that extrapolation or interpolation of term values using a polynomial expression in Z, the nuclear charge, gave very good results. It was thus possible to use for this work the same computer programme developed for wavelength measurement. New lines of Neon, Argon and Xenon are listed in Tables 1, 2 and 3 together with their classifications where available. The relative

intensities have been estimated from microphotometer traces of the spectra. The only lines of Neon IX measured were those at 13.44 Å and 13.55 Å which have been previously observed by Jahoda, Ribe, Sawyer and Stratton (1961).

The Neon lines could be predicted accurately by isoelectronic interpolation and in all cases the calculated values are within the experimental errors. In Argon this was not always the case, and there are several lines in which the experimental values are far more reliable. In particular, the Argon X lines at 165.57 Å and 170.65 Å could not be extrapolated accurately and the experimental value of 604060 ± 75 cm^{-1} that these give for the $2s\ 2p^6\ {}^2S$ level is an important factor in completing the term scheme for this ion. In the case of Argon there are many lines which have been measured, but whose classifications have not been established. The wavelengths and, in some cases, probable degree of ionization are listed with their intensities in Table 2. The Xenon spectrum is very complex and contained some 240 lines in the region 80 Å to 300 Å. Only the two strongest lines have been classified. These are listed in Table 3.

5. CONCLUSIONS

The possibility of studying spectra down to 13 Å using ruled gratings has been demonstrated. With the plasma devices now in use for fusion research this brings a large number of new inert gas spectra within the range of study. The present work has surveyed many of the Neon and Argon lines. A great deal of further work is necessary to extend this to the other inert gases and to improve the range and accuracy of the measurements.

6. ACKNOWLEDGMENTS

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TABLE 1

Neon Lines. Accuracy ± 0.05 Å

	λ(Å)	Int.	Classification
Neon VII	97.54	7	$2s^2\ {}^1S - 2s3p\ {}^1P^o$
	75.78	3	$2s^2\ {}^1S - 2s4p\ {}^1P^o$
	127.65	5	$2s2p\ {}^1P^o - 2s3s\ {}^1S$
	116.66	7	$2s2p\ {}^1P^o - 2s3d\ {}^1D$
	89.41	4	$2s2p\ {}^1P^o - 2s4d\ {}^1D$
	80.62	3	$2s2p\ {}^1P^o - 2s5d\ {}^1D$
	76.58	2	$2s2p\ {}^1P^o - 2s6d\ {}^1D$
	107.07	4	$2s2p\ {}^1P^o - 2p3p\ {}^1P$
	111.78	6	$2p^2\ {}^1D - 2p3d\ {}^1F^o$
	115.97	6	$2p^2\ {}^1D - 2p3d\ {}^1D^o$
	121.68	7	$2p^2\ {}^1S - 2p3d\ {}^1P^o$
	134.82	2	$2p^2\ {}^1S - 2p3s\ {}^1P^o$
	115.36	7	$2s2p\ {}^3P^o_{1,0} - 2s3s\ {}^3S_1$
	115.52	7	$2s2p\ {}^3P^o_2 - 2s3s\ {}^3S_1$
	84.34	2	$2s2p\ {}^3P^o_2 - 2s4s\ {}^3S_1$
	106.07	9	$2s2p\ {}^3P^o_1 - 2s3d\ {}^3D_2$
	106.19	9	$2s2p\ {}^3P^o_2 - 2s3d\ {}^3D_3$
	82.26	6	$2s2p\ {}^3P^o_2 - 2s4d\ {}^3D_3$
	95.86	7	$2s2p\ {}^3P^o_2 - 2p3p\ {}^3D_3$
	74.97	3	$2s2p\ {}^3P^o_2 - 2p4p\ {}^3D_3$
	94.33	6	$2s2p\ {}^3P^o_2 - 2p3p\ {}^3P_2$
	94.99	4	$2s2p\ {}^3P^o_2 - 2p3p\ {}^3S_1$
	110.60	7	$2p^2\ {}^3P_2 - 2p3d\ {}^3D^o_3,\ {}^3P^o_2$
	120.32	5	$2p^2\ {}^3P_2 - 2p3s\ {}^3P^o_2$

TABLE 1
(Continued)

	λ(Å)	Int.	Classification
Neon VIII	88.11	7	$2s\ ^2S - 3p\ ^2P^o$
	67.39	3	$2s\ ^2S - 4p\ ^2P^o$
	60.81	2	$2s\ ^2S - 5p\ ^2P^o$
	57.79	1	$2s\ ^2S - 6p\ ^2P^o$
	56.10	1	$2s\ ^2S - 7p\ ^2P^o$
	102.89	5	$2p\ ^2P^o_{1/2} - 3s\ ^2S_{1/2}$
	103.10	6	$2p\ ^2P^o_{1\frac{1}{2}} - 3s\ ^2S_{1/2}$
	74.64	3	$2p\ ^2P^o_{1\frac{1}{2}} - 4s\ ^2S_{1/2}$
	98.11	7	$2p\ ^2P^o_{1/2} - 3d\ ^2D_{1\frac{1}{2}}$
	98.27	7	$2p\ ^2P^o_{1\frac{1}{2}} - 3d\ ^2D_{1\frac{1}{2},2\frac{1}{2}}$
	73.55	4	$2p\ ^2P^o - 4d\ ^2D$
	65.89	2	$2p\ ^2P^o - 5d\ ^2D$
	62.36	1	$2p\ ^2P^o - 6d\ ^2D$
	60.45	1	$2p\ ^2P^o - 7d\ ^2D$

TABLE 2

Argon Lines. Accuracy ± 0.03 Å except where indicated

	λ(Å)	Int.	Classification
Argon IX	42.56	2	$2p^6 - 3d\ [\frac{1}{2}]^o$
	42.02	2	$2p^6 - 3d\ [1\frac{1}{2}]^o$
	41.48	6	$2p^6 - 3d'[1\frac{1}{2}]^o$
	35.28	3	$2p^6 - 4d\ [1\frac{1}{2}]^o$
	35.02	7	$2p^6 - 4d'[1\frac{1}{2}]^o$
	32.64	4	$2p^6 - 5d'[1\frac{1}{2}]^o$
	31.66	7	$2p^6 - 6d\ [1\frac{1}{2}]^o$
	31.52	6	$2p^6 - 6d\ [1\frac{1}{2}]^o$
Argon X	44.49	9	$2p^5\ {}^2P^o_{1\frac{1}{2}} - 2p^4({}^3P)3s\ {}^4P_{2\frac{1}{2}}$
	44.26	9	${}^2P^o_{1\frac{1}{2}} - {}^4P_{1\frac{1}{2}}$
	44.67	8	${}^2P^o_{\frac{1}{2}} - {}^4P_{1\frac{1}{2}}$
	43.93	9	$2p^5\ {}^2P^o_{1\frac{1}{2}} - 2p^4({}^3P)3s\ {}^2P_{1\frac{1}{2}}$
	43.72	7	${}^2P^o_{1\frac{1}{2}} - {}^2P_{\frac{1}{2}}$
	44.07	7	${}^2P^o_{\frac{1}{2}} - {}^2P_{\frac{1}{2}}$
	42.96	5	$2p^5\ {}^2P^o_{1\frac{1}{2}} - 2p^4({}^1D)3s\ {}^2D_{1\frac{1}{2},2\frac{1}{2}}$
	43.29	8	${}^2P^o_{\frac{1}{2}} - {}^2D_{1\frac{1}{2}}$
	41.56	4	$2p^5\ {}^2P^o_{1\frac{1}{2}} - 2p^4({}^1S)3s\ {}^2S_{\frac{1}{2}}$
	41.89	2	${}^2P^o_{\frac{1}{2}}\ {}^2S_{\frac{1}{2}}$
	165.57 (± 0.05 Å)	4	$2p^5\ {}^2P^o_{1\frac{1}{2}} - 2s2p^6\ {}^2S_{\frac{1}{2}}$
	170.65 (± 0.02 Å)	2	${}^2P^o_{\frac{1}{2}} - {}^2S_{\frac{1}{2}}$
	45.05	7	$2s2p^6\ {}^2S_{\frac{1}{2}} - 2s2p^5({}^3P)3s\,{}^2P^o_{1\frac{1}{2}}$
	44.85	6	${}^2S_{\frac{1}{2}} - {}^2P^o_{\frac{1}{2}}$

TABLE 2
(Continued)

	λ(Å)	Int.	Classification
Argon XI	39.74	5	$2p^4\ ^3P_2 - 2p^3(^4S)3s\ ^3S^o_1$
	39.95	3	$^3P_1 - \quad ^3S^o_1$
	40.02	2	$^3P_0 - \quad ^3S^o_1$
	39.50	6	$2p^4\ ^1D - 2p^3(^2D)3s\ ^1D^o$
	35.39	7	$2p^4\ ^3P_2 - 2p^3(^4S)3d\ ^3D^o_{1,2,3}$
	35.58	6	$^3P_{0,1} - \quad ^3D^o_{1,2}$
	34.24	7	$2p^4\ ^3P_2 - 2p^3(^2D)3d\ ^3P^o_2$
	34.35	8	$^3P_2 - 2p^3(^2D)3d\ ^3D^o_{1,2,3}$
	34.52	7	$^3P_{0,1} - \quad ^3D^o_{1,2}$
Argon XII	34.68	7	$2p^3\ ^4S^o_{1\frac{1}{2}} - 2p^2(^3P)3s\ ^4P_{2\frac{1}{2}}$
	34.79	6	$^4S^o_{1\frac{1}{2}} - \quad ^4P_{1\frac{1}{2}}$
	34.88	5	$^4S^o_{1\frac{1}{2}} - \quad ^4P_{\frac{1}{2}}$
	45.41	4	$2p^3\ ^2D^o - 2p^2(^1D)3s\ ^2D$
	46.71	5	$2p^3\ ^2P^o_{1\frac{1}{2}} - 2p^3(^1D)3s\ ^2D_{2\frac{1}{2}}$
			Probable ion
Argon (Unclassified)	39.82	5	XI
	39.34	3	
	38.88	5	
	38.64	7	X
	38.40	5	X
	38.22	6	X
	38.04	3	
	37.81	4	
	37.59	7	X

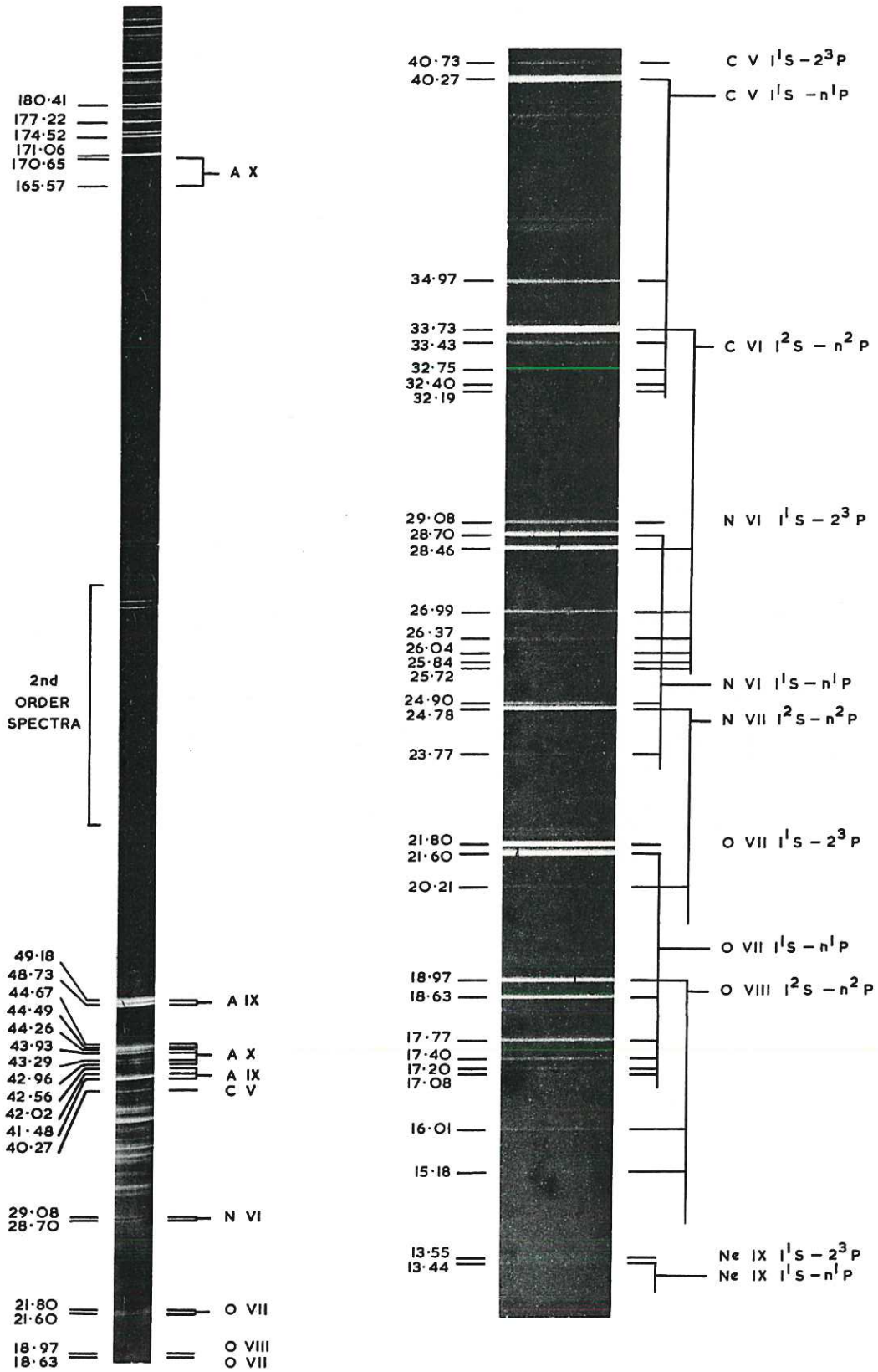
TABLE 2
(Continued)

	λ(Å)	Int.	Probable ion
Argon (Unclassified)	37.42	7	X
	36.98	4	IX
	36.78	5	IX
	36.67	5	IX, X
	36.55	4	IX, X
	35.82	5	IX
	32.54	5	IX, X
	32.46	5	
	32.28	5	
	31.97	5	
	31.82	4	
	31.46	6	
	31.36	7	
	30.95	5	IX, X
	30.59	3	
	30.26	3	
	30.06	2	
	29.88	3	
	29.57	5	
	29.38	5	
	27.94	4	
	27.80	4	
	27.54	4	
	27.40	4	
	26.36	4	
	26.23	2	
	26.04	3	
	25.71	4	
	25.59	4	
	25.25	4	

TABLE 3

Xenon Lines

Xenon IX	165.31 ± 0.02	$4d^{10}\ {}^1S_0 - 4d^9({}^2D)5p\ {}^1P_1^o$
	161.73 ± 0.02	$4d^{10}\ {}^1S_0 - 4d^9({}^2D)5p\ {}^3D_1^o$



CLM-P40 Fig. 1

Grazing incidence spectra showing (a) ZETA discharge containing 5% Argon, and (b) MAGGI I Thetatron containing 5% of Neon