192
LA-6275-MS

Informal Report

UC-20

Reporting Date: March 1976

Issued: March 1976

MASTER

**Vacuum Ultraviolet Emission from
Argon, Krypton, and Xenon in a
Radial-Viewed Theta Pinch**

by

R. Engleman, Jr.

D. B. Thomson

D. A. Monaghan

An Affirmative Action/Equal Opportunity Employer

UNITED STATES
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
CONTRACT W-7405-ENG. 33

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22151
Price: Printed Copy \$3.50 Microfiche \$2.25

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.

VACUUM ULTRAVIOLET EMISSION FROM ARGON, KRYPTON, AND XENON
IN A RADIAL-VIEWED THETA PINCH

by

R. Engleman, Jr., D. B. Thomson, and D. A. Monaghan

ABSTRACT

Vacuum ultraviolet line emission from argon, krypton, and xenon (5% in deuterium) has been observed from a plasma (~ 50 eV and $n_e \sim 10^{17}/\text{cm}^3$) produced by the Scyllar linear theta-pinch device. More than 50 emission lines in the 30- to 500-A region have been measured for each gas mixture. Some lines have been identified as due to Ar VII through XI, Kr IX and X, and Xe IX, but many lines remain unassigned.

I. INTRODUCTION

The Scyllar device, a large linear θ pinch, has been used to observe argon-, krypton-, and xenon-seeded plasma radiation in the vacuum ultraviolet (VUV).¹ This was done to examine the effects of readily introduced high-Z impurities on the θ pinch as reflected in the VUV emission spectrum. Extensive work² with neon-seeded Scyllar plasmas has defined the general behavior with a low-Z impurity. Similar studies with smaller θ pinches and argon- or xenon-seeded plasmas have been described earlier.³

We have used a radial view of the Scyllar plasma to obtain VUV spectra of the high-Z elements. Our earlier studies² on neon seeded plasmas have shown the advantages of using a radial view of the plasma emission compared to the more conventional axial view. The radial view appears to give spectra less contaminated by emission from the cooler plasma that may be ejected from the ends of the pinch region. The radial view appears to give

better defined plasma conditions for emission intensity measurements and result in better discrimination of ion stage in the emitted line radiation.

II. EXPERIMENTAL TECHNIQUES

Scyllar is a large linear θ pinch for use in plasma radiation studies and a detailed description has been given elsewhere.² For the work described here, Scyllar was operated at one-third capacitance (42 kJ), which yields an axial drive field of about 45 kG with a risetime of about 2 μsec . The one turn θ -pinch coil is 250 mm long with an internal diameter of 82 mm. A ceramic discharge tube was used with a 12 mm inside diameter ceramic tube protruding at right angles from it and projecting through a small hole centered in the side of the θ -pinch coil. This smaller tube provides the vacuum line of sight between the plasma and the spectrograph. This arrangement is portrayed schematically in Fig. 1.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Fig. 1. Schematic diagram of the radial-viewed theta pinch arrangement with the vacuum spectrograph.

We obtained emission spectra with a SPEX 2.2-m grazing incidence vacuum spectrograph equipped with a 1200-line/mm B & L grating operating at 85° angle of incidence. The instrumental resolution was about $0.2 \text{ \AA}$ and the wavelength accuracy was $0.1 \text{ \AA}$ or better with a wavelength coverage between 30 and $500 \text{ \AA}$. Spectra were taken on either Kodak SWR or SC-7 film. All spectra were time-integrated views of the plasma and generally required 4 or more discharges for good darkening of the film.

In the present experiments, mixtures of about 5% Ar, Kr, or Xe in deuterium were used at initial filling pressures of about 0.02 kPa (0.15 torr). Similar spectra using neon mixtures were also obtained for use as wavelength standards. Extensive diagnostic work^{2,4} on helium-neon plasmas at somewhat higher pressures and with a 90-kG axial drive field showed that the plasma is stable for about one μsec , has a peak temperature of about 40 eV, and $n_e \sim 5 \times 10^{17}/\text{cm}^3$. Lower filling pressure should bring up the peak temperature, while the presence of high-Z elements would be expected to lower the peak temperature.

Most spectra were measured on an automatic comparator-densitometer,⁵ although a few were measured by hand and intensities estimated by eye. Wavelength calibrations were obtained from overlapping Ne lines, impurity lines, and unambiguously identified rare gas lines. No attempt was made to obtain line intensities corrected for film response or other such factors.

III. RESULTS

Figure 2 shows a composite of typical rare gas plasma emission spectra obtained in this study. Only a few lines of each species have been marked, but are sufficient to establish a rough wavelength scale. A detailed list of the Ne wavelengths can be found in our earlier work.² The line lists of Tables I, II, IV, and V give the wavelengths in angstroms and intensities in approximate relative log units. The following abbreviations are used where necessary:

B	Broad	VS	Very strong
BL	Blend	S	Strong
ST	Saturated	M	Medium
		W	Weak

Line assignments have generally been taken from the compilation of Kelly and Palumbo.⁶

A. Argon

Approximately 50 emission lines were observed and measured from the spectrum of the argon plasma. Some of these were identified as impurity lines and 26 were identified as known transitions of Ar VII through XI (Table I). Impurity lines were generally recognized when they were present in all the different plasma spectra. The remaining lines do not correspond to known lines of argon. The apparent absence of the lower ion stages is similar to our earlier observation with the radial viewed He-Ne plasmas.² Another spectrum of argon, which showed the shortest wavelengths particularly well, was measured by hand and is shown in Table II. A LTE calculation⁷ of Ar ion stages expected under these conditions (Fig. 3) indicates a peak plasma temperature perhaps as high as 50 eV. Figure 4 shows a simple diagram of the known energy levels of Ar VIII with the transitions observed in this study marked.

Fig. 2. Vacuum ultraviolet emission spectra of argon, krypton, and xenon with a neon reference spectrum. Only one of the several common impurity lines is marked with a dashed line.

Fig. 3. Ionic abundance calculation of various argon species for $n_e = 10^{17}/\text{cm}^3$. Emission lines of the starred species were observed in the present experiments.

Fig. 4. Level diagram for Ar VIII with all known transitions shown. Starred transitions were identified in the present study, although not all close doublets were resolved. Transitions are in units of angstroms, whereas the vertical scale is in units of 10^4 cm^{-1} .

In order to compare wavelengths and intensities with theory, ab initio calculations for Ar VIII were obtained⁸ using the atomic level codes of Cowan.⁹ These results are presented in Table III along with the experimental values from Kelly and Palumbo.⁶ Adjustments to wavelength and intensity values have been made in light of the limited experimental resolution available in the present measurements. The wavelength agreement is acceptable and averages under 10% between experimental and calculated. The two experimental intensity scales are not directly related, but reasonable agreement also appears there. The calculated gf values would need a thermal Boltzmann factor included before any comparison should be made with experiment. However, for close lying levels, such as the (Jp-4d)'s at 179.4 and 180.3 Å, the intensities are in the right order.

B. Krypton

Of the 59 lines measured from the krypton plasma spectra, 11 were assigned to known transitions of Kr IX and X (Table IV). Except for some impurity lines, the remaining ones have not yet been assigned and may belong to other ion stages of Kr. Ab initio calculations⁸ have also been made for some ion stages of Kr, but their application to actual spectra is complicated and has not yielded results.

C. Xenon

The xenon plasma spectra yielded about 70 lines as given in Table V. Outside of some impurity lines and two strong Xe IX lines (161.73 and 165.31 Å),³ the lines are unassigned. The dense clusters of lines around 110 and 148 Å are most interesting, with what appears to be an emission edge at 109.9 Å.

IV. CONCLUSIONS

It appears that the Scyllar θ-pinch device can operate successfully with high-Z elements and should provide a useful source of VUV line emission for possible analysis of the spectra of highly stripped ions. Emission spectra of almost all high-Z elements can probably be obtained under similar plasma conditions by seeding the base gas with an appropriate volatile compound, as has been done with iron carbonyl.^{4,10} Further work, perhaps

with time-resolved spectra, would be useful to limit the number of ion stages appearing on a given spectrum and thus considerably simplify the analysis.

ACKNOWLEDGMENTS

The authors wish to thank M. R. McClannahan for his efforts in all phases of the experimental work. We are also most appreciative of the work of A. G. Bailey in the design, construction, and testing of new control circuits and other components of the capacitor bank.

REFERENCES

1. R. Engleman, Jr., D. B. Thomson, and D. A. Monaghan, "VUV Emission from Ar, Kr, and Xe in a Radial-Viewed θ-Pinch," *Bull. Am. Phys. Soc.*, Ser. II, 19, No. 9, 892 (1974) paper 3F6
2. D. B. Thomson, A. G. Bailey, and R. Engleman, Jr., "Vacuum Ultraviolet Emission from a Neon-Seeded Theta Pinch," Los Alamos Scientific Laboratory report LA-5466-MS (1974).
3. B. C. Fawcett, A. H. Gabriel, B. B. Jones and N. J. Peacock, *Proc. Phys. Soc.* 84, 257 (1964); N. J. Peacock, R. D. Cowan and G. A. Sawyer, *Proc. 7th Inter. Conf. on Phenomena in Ionized Gases*, Vol. 2, page 599 (1965).
4. D. B. Thomson, L. A. Jones, A. G. Bailey, and R. Engleman, Jr., "Characteristics of High Density Theta Pinches Seeded with Selected High-Z Elements," Presented at the Third Topical Conference on Pulsed High Beta Plasmas, UKAEA Culham Laboratory, England. Sept. 9-12 (1975). To be published in *J. Plasma Physics*.
5. D. W. Steinhilber, K. J. Fisher, and R. Engleman, Jr., *Chem. Instru.* 3, 141 (1971).
6. R. L. Kelly and L. J. Palumbo, "Atomic and Ionic Emission Lines Below 2000 Angstroms-Hydrogen through Krypton," Naval Research Laboratory report NRL-7599 (1973).
7. A. L. Merts and N. H. Magee, Jr., Los Alamos Scientific Laboratory, private communication (1974).
8. L. J. Radziemski, Los Alamos Scientific Laboratory, unpublished work.
9. R. D. Cowan, *J. Opt. Soc. Am.* 58, 808 (1968).
10. L. L. House, W. A. Deutschman, and G. A. Sawyer, *Astrophys. J.* 140, 814 (1964).

TABLE I

EMISSION LINES FROM AN ARGON-SEEDED PLASMA

λ	I	Assignment
$48.55 \pm .05 \text{ \AA}$	1.5 B	
48.71	2.5	48.73 Ar IX
49.20	2.6	49.18 Ar IX
97.44	0.7	
98.34	0.5	
100.09	0.8	
120.28	1.5	120.157 Ar VIII
120.96	1.0	
123.14	0.5	
130.01	1.0	129.872 O VI ?
137.17	0.6	
138.09	1.0	137.926 Ar VIII
138.66	1.8	138.44 Ar VIII
147.09	0.4	
150.30	2.2	150.089 O VI
150.61	0.5	
152.03	3.8	151.879 Ar VII
159.12	5.0	159.175 Ar VIII
159.40	3.5 B	159.36 O V
165.64	6.3 ST	165.53 Ar X
170.69	6.0 ST	170.63 Ar X
172.10	0.5	172.169 O V
173.10	3.8	173.082 O VI
175.51	1.2	175.67 C V ?
179.38	4.0	179.400 Ar VIII
180.26	5.0	180.254 Ar VIII
180.73	1.3	180.719 Ar VII
184.25	3.0	184.29 Ar VIII
184.60	1.2	184.51 Ar XI
187.08	1.2	187.08 Ar XI
188.80	3.5	188.82 Ar XI
189.58	0.8	189.57 Ar XI
190.96	1.0	190.96 Ar XI
192.04	0.5	192.04 Ar VII
192.69	1.8	192.635 Ar VII
194.13	1.0	194.09 Ar XI
198.55	2.2	

TABLE I (Continued)

λ	I	Assignment
$202.61 \pm .05 \text{ \AA}$	1.1	Ar VIII ?
203.73	0.4	Ar VIII ?
209.27	1.2	209.29 N V ?
224.70	1.3	
229.45	2.5	229.437 Ar VIII
230.85	3.5	230.875 Ar VIII
247.99	M	
251.19	W	250.940 Ar VII ?
260.70	VS	260.29 Ar VIII ?
298.37	M	297.70 Ar VII ?
332.41	M	
342.70	W	

TABLE II

EMISSION LINES OF ARGON

λ	Assignment
$33.5 \pm 0.1 \text{ \AA}$	33.53 Ar XI
34.8	35.02 Ar IX
37.3	37.43 Ar X
38.3	38.33 Ar XI
40.2	40.04 Ar XI
41.5	41.5 Ar IX
42.0	42.02 Ar IX
42.6	42.56 Ar IX
43.0	42.94 Ar X
43.2	43.27 Ar X
43.9	43.92 Ar X
44.2	44.27 Ar X
44.5	44.63 Ar X
45.1	45.03 Ar X
48.8 VS	48.73 Ar IX
49.3 VS	49.18 Ar IX

TABLE III
COMPARISON OF DATA AND CALCULATION FOR Ar VIII

Wavelength (Å)			Intensity			Assignment
This work	Kelly	Cowan	This work	Kelly	Cowan (gf)	
120.28	120.09	122.58	1.5	150	0.18	3s-5p
138.09	137.93	137.30	1.0	150	0.13	3p-5d
138.66	138.44	137.84	1.8	250	0.25	3p-5d
159.42	159.18	158.00	5.0	650	0.64	3s-4p
179.38	179.40	178.40	4.0	500	0.31	3p-4d
180.26	180.25	179.29	5.0	750	0.61	3p-4d
184.25	184.27	184.00	3.0	400	1.72	3d-5f
229.45	229.44	228.05	2.5	250	0.17	3p-4s
230.85	230.88	229.55	3.5	350	0.34	3p-4s
260.70	260.30	260.16	VS	500	8.5	3d-4f

TABLE IV

TABLE IV (Continued)

EMISSION LINES FROM A KRYPTON-SEEDED PLASMA			λ	I	Assignment
λ	I	Assignment			
79.51 $\pm$.05Å	0.3 B		114.94 $\pm$.05Å	1.3 ST	114.948 Kr IX
86.09	0.3 B		115.73	1.4 ST	115.741 Kr IX
86.81	1.0 B		117.74	0.3	117.710 Kr IX
88.87	0.5		119.51	0.1	
89.36	0.5		121.07	0.1	
89.79	0.5		121.66	0.1	
90.42	0.7 B		124.88	0.4	
92.24	0.4		125.47	0.1	
93.51	0.7		130.00	0.3	
95.68	0.3		150.38	1.0	150.089 O VI
96.35	0.3		173.10	1.3	173.08 O VI
96.69	0.3		181.66	0.6	
98.15	0.7 B		182.89	0.4	
98.96	1.2		184.08	0.2	
99.40	0.3	99.57 Kr X	185.44	0.1	
99.81	0.3	99.86 Kr X	186.13	0.3	
100.36	0.3	100.30 Kr X	191.89	0.1	
101.86	0.3	101.20 Kr X	192.80	0.3	
102.48	0.3	102.30 Kr X	198.51	0.3	
103.00	0.3	102.86 Kr X	209.29	0.8	209.29 N V
103.34	0.3	103.27 Kr X	229.89	0.2	
103.76	0.3	103.60 Kr X	231.43	0.3	
104.45	0.3		244.85	VW	
106.22	0.7		250.55	VW	
108.39	0.3		251.85	W	
108.81	0.3		269.35	M	
110.41	0.3		271.35	VW	
110.92	0.3		310.85	W	
			318.85	W	

TABLE V

EMISSION LINES FROM A XENON-SEEDED PLASMA		
λ	I	Assignments
83.16 $\pm$.1 $\text{\AA}$	0.8	
83.70	0.5	
92.41	0.8	
99.68	0.5	
100.76	0.2 B	
109.89	0.2 B	Edge ?
111.82	1.0	
112.80	1.1 B	
113.60	0.8 B	
114.55	0.5	
114.93	0.3	
118.34	1.2	
118.91	0.3	
121.73	0.6 B	
122.69	0.6	
123.47	0.4	
130.48	0.7 B	129.872 O VI ?
131.58	0.8 B	
132.33	0.5 B	
132.65	0.6 B	
133.16	1.0 B	
134.30	1.8 B	
135.61	1.0 B	
136.40	0.2	
136.88	0.4	
137.71	0.2	
138.31	0.3	
140.38	0.2	
141.38	0.7	
142.98	0.9	
144.18	0.8	
144.71	1.1	
145.51	1.3 BL	
146.00	0.8 BL	
147.21	1.5 BL	
147.53	2.0 BL	

TABLE V (Continued)

λ	I	Assignments
147.97 $\pm$.1 $\text{\AA}$	1.4 BL	
148.58	1.6	
149.03	1.3	
149.76	1.6	
150.24	1.7	150.089 O VI
151.46	1.5	
151.79	1.4	
152.60	0.4	
154.36	1.2 B	
158.91	0.3	
159.53	0.3	
161.73	2.5	161.73 Xe IX
165.31	2.8	165.31 Xe IX
166.70	0.3	
170.93	1.1	
173.08	1.8 BL	173.08 O VI
173.45	0.8 BL	
174.25	0.3	
176.03	0.5	
177.30	0.8	
177.77	1.0	
179.76	0.4	
181.89	0.3	
184.12	0.3	
184.76	0.3	
186.22	0.7	
193.04	1.3	
196.65	0.6	
197.44	0.4	
200.94	0.3	
203.94	0.4	
209.29	1.2	209.29 N V
221.66	1.0	
225.19	0.8	
265.20	0.4	
281.65	1.0	