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THE SPECTRUM OF MULTIPLY-IONIZED ARGON BETWEEN 20 AND 40 ANGSTROMS

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by

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ABSTRACT

Valency and inner shell transitions in multiply ionized argon have been excited in the transient pinch of a 'Plasma Focus' discharge. Hartree-Fock calculations have been made to identify the levels involved.

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1. INTRODUCTION

No observation of spectra originating from stages of ionization of argon higher than Ar IX is reported in Moore's tables of Atomic Energy Levels, Vol.I (1958). Some improvement in the situation regarding the multiply ionized argon spectrum is found if the more recent tables of Kelly (1968) are consulted, owing to the work of Fawcett, Jones, Gabriel, and Peacock (1964), Fawcett (1965) and the computations of Garcia and Mack (1965). However, the tables of Kelly still contain no data on stages of ionization between Ar XIII and Ar XV inclusive and feature many unclassified lines between 25 and 40 Å.

Argon is one of the less prominent elements in the solar spectrum: it is not listed in the table of fifty seven elements in the sun's atmosphere given by St John, Moore, Ware, Adams, and Babcock in the introduction to the revised Rowland Table (1928). With the advent of rocket spectroscopy, the Ar I resonance line at 1067 Å has been observed, and is contained in Jordan's list (1965) of solar emission lines between 1994 Å and 13·7 Å as a firm assignment (intensity < 1), together with tentative identifications of Ar I transitions at 1048 and 894 Å. Tentative identifications of Ar III, V, VIII, IX, X and XII lines are also present in Jordan's list. More recently, Tousey (1968) has tabulated Ar, X, XI, XIII, XIV and XV as ions with transitions detected in the sun at wavelengths below 2500 Å and Ar VIII as an ion whose presence was detected at XUV wavelengths. In the survey of coronal visible line identifications by Wagner and House (1968) the table of accepted coronal visible line identifications contains a line of Ar XV at 5926 Å.

Finally, the recent work of Peacock, Speer and Hobby (1969) has led to the identification of Ar XVII and Ar XVII and Ar XVIII emissions in data from the OSO V satellite (Neupert and Swartz 1970). Further work on the Ar XIII-Ar XVII spectra therefore seemed justified. We report here a new study of the multiply ionized argon spectrum excited in a 'Plasma Focus' discharge (Peacock, Speer and Hobby 1969). Hartree-Fock calculations of the transition energies have been made and a comparison with the observed spectra between 20 and 40 Å leads to identification of the resonance multiplets of the intermediate argon ions, Ar X to Ar XVI.

2. EXPERIMENTAL METHOD AND RESULTS

The Plasma Focus apparatus used in our experiments and observations of the argon spectrum in the 3-4 Å range have been described previously (Peacock, Speer and Hobby, 1969), and the presence of stages of ionization as high as Ar XVIII was established by the analysis of crystal dispersion spectra, showing the 1s-2p transition predicted by Garcia and Mack (1965).

In the present experiments, the spectrum of multiply ionized argon between 20 and 40 Å was photographed using a 2 metre spectrograph with the entrance slit at 2^{o} grazing angle to the grating surface. A typical spectrum is reproduced in Figure 1, and, although no filter was used, order overlap is no problem below 40 Å.

Because debris from the Plasma Focus electrodes clogged the entrance slit to the spectrograph, the slit was set much wider (~ 10 microns) than for optimum focus. The wavelength resolution in this study is therefore relatively poor ($\delta\lambda = \pm$ 0·10 Å). Many of the weaker components of the multiplets and, in some cases the whole multiplet structure, are not resolved. The strong resonance transitions are, however, readily identifiable in all the argon ions isoelectronic with the second period, and the identifications will prove useful in any future higher resolution study of argon.

Lines of C V, C VI, N VI, N VII, and O VII in the first and second orders are used as standards, and fitted to a polynomial with a deviation of 0·0185 Å. The argon emission lines were measured with a Zeiss Abbe comparator and are listed in the first column of Table I.

3. ANALYSIS

As we have previously commented (Connerade, Peacock and Speer, 1970) the identification of XUV emission lines due to valency and inner shell transitions in highly stripped ions is greatly assisted by direct, ab initio calculations using the Hartree-Fock technique.

Our procedure has been the same as in the reference cited above (Connerade et al. 1970): we have used a Hartree-Fock programme due to Froese-Fisher (1969), allowing for structure in LS coupling using the tables published by Slater (1960). As an independent check on some of the calculations, Bacher and Goudsmit (1934) extrapolations were used (Connerade 1970).

In the wavelength range 20-40 Å, the structure is sufficiently open for departures from the LS coupling approximation to become significant. Also, we do not expect the Hartree-Fock technique to yield as close agreement with experiment as in the 10-17 Å region of our previous study. In general, we have been satisfied with wavelength agreements within about ± 0·2 Å and, when many numerical coincidences occurred, we have given preference to 2p-3d transitions between valence electrons which are expected (cf. Fawcett et al. 1964) to be more intense in laboratory plasma devices. Where previous identifications had been made, we were in good agreement with them generally to within 0·1 Å. An exception occurred for two lines reported by Fawcett et al (1964) at 46·71 and 45·4 Å and identified by them as Ar XII 2p-3s transitions: our calculations placed these transitions at about 35 Å, (Table I). Because of the overall agreement between the observed and calculated wavelengths in this work, and particularly for the other 2p-3s multiplets, it is evident that the original wavelengths were wrongly identified.

Nearly all of the 60 or so lines observed could be classified as 2-3 excitation in stages of ionization ranging from Ar IX to Ar XVIII. No stage of ionization was admitted which did not exhibit the optical 2p-3d transitions. Several examples of inner shell excitation were found.

Our results with interpretations are presented in Table I: the first two columns contain the present (Plasma Focus) observations. In the third, we have listed previous experimental wavelengths close to ours, taken from the work of Fawcett et al (1964) and Garcia and Mack (1965). In the last column wavelengths corresponding to our assignments are given. All the wavelengths of the last column are theoretical and result from the computations described above, excepting one, due to the calculations of Garcia and Mack (denoted by an asterisk). The intensities in column 2, Table I, are derived from photometric measurements of the maximum blackness on the photographic plate. The figures in this column are normalised to 1000 and have not been corrected for transmission of the spectrograph.

4. CONCLUSIONS

The Plasma Focus device has been used as a spectroscopic source for studying the emission spectrum of highly ionized argon between 40 Å and 20 Å. In this wavelength region lies most of the resonance lines of the argon ions isoelectronic with the second period elements. In contrast to other sources, all the argon ions isoelectronic with this period are produced in the Focus. The indentifications extend, and are complementary to, previous publications on more and less-highly stripped argon ions.

The emission lines are identified mainly by Hartree-Fock calculations of the levels. While the measure of agreement between the calculations and the observations in such that alternative identifications can be admitted, the observed intensities of the lines generally leads to unambiguous classification. The limited wavelength resolution in the plates justifies this procedure.

ACKNOWLEDGEMENTS

Thanks are due to Professor Froese-Fischer for the loan of her Hartree-Fock programme. The calculations were carried out on the IBM 1130 computer at ESRIN.

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TABLE I: <u>INTERPRETATION OF THE PLASMA FOCUS ARGON SPECTRUM</u>

λ Plasma Focus Å	Intensity	λ Nearest Previous Observation or Calculation Å	Previous Assignment	Ion Stage for Present Assignment	Present Assignments (square brackets indicate less likely identifications i.e. weaker transitions)	λ Present Assignment Å
B20·16	50	20·16*	Ar XVIII 2(s,p)-3(s,p,d)*	Ar XVIII	2(s,p)-3(s,p,d)	20·16*
				Ar XIV	$2s^2 2p-2s^2 4d$	21·24
21·17	100	–	– –	[Ar XIV	$2s^2 2p-2s^2 4s$	21·62]
				[Ar XVII	$1s2s\,^3S-1s3p\,^3P$	21·69]
22·4	40	–	– –	Ar XVII	$1s2p\,^3P-1s3d\,^3D$	22·29
					([$1s2s\,^1S_o-1s3p\,^1P_1$	22·37]
				[Ar XVII	$1s2p\,^1P-1s3d\,^1D$	22·89]
					$2p^2\ ^3P_o-2p4d\,^3P$	22·94
B23·03	50	–	– –	Ar XIII	$2p^2\ ^3P_1-2p4d\,^3P$	22·97
					$2p^2\ ^3P_2-2p4d\,^3P$	23·05
B23·39	50	–	– –	Ar XIII	$2p^2\ ^1D-2p4d\,^1P$	23·38
					($2p^2\ ^1D-2p4d\,^1D$	23·45
				[Ar XVI	2s-3p	23·62]
					$2p^2\ ^3P_1-2p4s\,^3P_2$	23·48]
23·57	200	–	– –		$2p^2\ ^3P_1-2p4s\,^3P_2$	23·56]
				[Ar XIII	$2p^2\ ^3P_o-2p4s\,^3P_1$	23·57]
					$2p^2\ ^3P_1-2p4s\,^3P_o$	23·61]
					$2p^2\ ^3P_2-2p4s\,^3P_1$	23·65]
23·93	50	–	– –	Ar XIII	$2p^2\ ^1S-2p4d\,^1P$	23·96
24·35	80	–	– –	?	?	?
24·6	80	–	– –	[Ar XIII	$2p^2\ ^1S_o-2p4s\,^1P_1$	24·53]
					($2p^2\ ^1S_o-2p4s\,^3P_1$	24·61]
				Ar XII	$2p^3\ ^4S-2p^2 4d\,^4P$	24·87

λ Plasma Focus Å	Intensity	λ Nearest Previous Observation or Calculation Å	Previous Assignment	Ion Stage for Present Assignment	Present Assignments (square brackets indicate less likely identifications i.e. weaker transitions)	λ Present Assignment Å
				(Ar XVI	2p-3d	25·03
25·05	100	-	- -		$2s^2\ ^1S_0-2s3p^1P_1$	25·01]
				[Ar XV	($2s_2^2\ ^1S_0-2s3p^3P_1$	25·12]
25·3	60	25·25†	unclassified†	Ar XIV	$2s^22p^2P_{1/2}-2s2p3p^2P_{1/2}$	25·42
25·56	60	25·59†	unclassified†	Ar XIV	$2s^22p^2P_{3/2}-2s2p3p^2P_{1/2,3/2}$	25·58
25·72	40	25·71†	unclassified†	Ar XV	$2s2p^3P_0-2s3d^3D_1$	25·74
25·84	60	-	-	Ar XV	$2s2p^3P_1-2s3d^3D_{1,2,3}$	25·79
26·00	80	26·04†	unclassified†	Ar XV	$2s2p^3P_2-2s3d^3D_{1,2}$	25·90
B26·36	110	26·36†	unclassified†	Ar XIII	$2s^22p^2\ ^3P-2s2p^23p^3S$	26·45
26·53	60	-	-	Ar XIII	$2s^22p^2\ ^3P-2s2p^23p\ ^3P,P,D$	26·68
26·72	40	-	-	Ar XIV	$2s^22p\ ^2P-2s2p3p^2P$	26·71
26·82	40	-	-	Ar XIII	$2s^22p^2\ ^1D-2s2p^23p\ ^1P,D$	26·92
27·17	60	-	-	Ar XIII	$2s^22p^2\ ^1D-2s2p^23p^1P$	27·18
27·41	120	27·40†	unclassified†	Ar XV	$2s2p^1P-2s3d^1D$	27·39⁰
27.44	120	-	-	Ar XIV	$2s^22p^2P_{1/2}-2s^23d^2D_{3/2}$	27·39⁰
27·60	100	27·54†	unclassified†	Ar XIV	$2s^22p^2P_{3/2}-2s^2\ 3d^2D_{3/2,5/2}$	27·56
				[Ar XII	$2s^22p^3\ ^2D-2s2p^33p^2P$	27·53]
				[Ar XIII	$2s^22p^2\ ^3P-2s2p^23p^3D$	27·62]
				[Ar XIII	$2s^22p^2\ ^3P-2s2p^23p^3D$	27·62]
					($2s^2\ 2p^2\ ^1S_0-2s2p^23p^1P_1$	27·69]
				(Ar XIII	$2s^22p^2\ ^1S-2s2p^23p^1P_1$	27·97
27·9	100	27·94†	unclassified†		($2s^22p^2\ ^1D-2s2p^23p^1P\ D\ F$	28·0
				Ar XII	$2s^22p^3\ ^2P-2s2p^3\ 3p^2P$	28·05
28·26	120	-	-	Ar XV	$2s2p^1P-2s3s^1S_0$	28·29
28·68	80	-	-	Ar XIII	$2s^22p^2\ ^1S_0-2s2p^23p^1P_1$	28·80

λ Plasma Focus Å	Intensity	λ Nearest Previous Observation or Calculation Å	Previous Assignment	Ion Stage for Present Assignment	Present Assignments (square brackets indicate less likely identifications i.e. weaker transitions)	λ Present Assignment Å
29·3	150	29·38†	unclassified†	Ar XIII	$2s^2 2p^2\ ^3P - 2s^2 2p3d\ ^3P$	29·28
				[Ar XIV	$2s^2 2p\ ^2P - 2s^2 3s\ ^2S$	29·23]
29·5	150	29·57†	unclassified†	Ar XI	$2s^2 2p^4\ ^3P - 2s2p^4 3p\ ^3S$	29·48
29·85	100	29·88†	unclassified†	Ar XIII	$2s^2 2p^2\ ^1D - 2s^2 2p3d\ ^1P$	29·89
30·21	100	30·26†	unclassified†	Ar XIII	$2s^2 2p^2\ ^1D - 2s^2 2p3d\ ^1D$	30·19
30·40	150	30·59†	unclassified†	[Ar XI	$2s^2 2p^4\ ^3P - 2s2p^4 3p\ ^3P$	30·48]
				Ar XII	$2s^2 2p^3\ ^2D - 2s^2 2p^2 3d\ ^2D$	30·51
30·65	150	-	-	Ar XII	$2s^2 2p^3\ ^2D - 2s^2 2p^2 3d\ ^2D$	30·73
				Ar XIII	$2s^2 2p^2\ ^1S_0 - 2s^2 2p3d\ ^1P_1$	30·85
31·10	200	30·95†	unclassified Ar IX,X?†	Ar XI	$2s^2 2p^4\ ^1D_1 - 2s2p^4 3p\ ^1P_1$	30·99
31·36	300	31·36†	unclassified†	Ar XI	$2s^2 2p^4\ ^1S_0 - 2s2p^4 3p\ ^1P_1$	31·13
31·47	300	31·46†	unclassified†	Ar XII	$2s^2 2p^3\ ^4S - 2s^2 2p^2 3d\ ^4P$	31·43
				Ar XI	[$2s^2 2p^4\ ^3P - 2s2p^4 3p\ ^3SPD$	31·44]
		31·52†	Ar IX $2p^6 - 2p^5 6d$†	Ar XIII	$2p^2\ ^3P_1 - 2s3s\ ^3P_2$	31·59
		31·66†	Ar IX2p6-2p⁵6d†		$2p^2\ ^3P_0 - 2p3s\ ^3P_1$	31·67
31·66	350				$2p^2\ ^3P_2 - 2p3s\ ^3P_2$	31·73
					$2p^2\ ^3P_1 - 2p3s\ ^3P_1$	31·74
		31·82†	unclassified†		$2p^2\ ^3P_1 - 2p3s\ ^3P_0$	31·81
31·94	200	31·97†	unclassified†		$2p^2\ ^3P_2 - 2p3s\ ^3P_1$	31·88
32·25	200	32·28†	unclassified†		$2p^2\ ^1D_2 - 2p3s\ ^1P_1$	32·28
				Ar X	$2s^2 2p^5\ ^2P - 2s2p^5 3p\ ^2S$	32·33
32·45	320	32·46†	unclassified†		$2s^2 2p^5\ ^2P - 2s2p^5 3p\ ^2P$	32·48
32·61	200	32·54†	unclassified Ar IX,X?		$2s^2 2p^5\ ^2P - 2s2p^5 3p\ ^2D$	32·54
32·70	230	32·64†	Ar IX $2p^6 - 2p^5 5d$†		$2s^2 2p^5\ ^2P - 2s2p^5 3p\ ^2S$	32·63
					$2s^2 2p^5\ ^2P - 2s2p^5 3p\ ^2P$	32·67
					$2s^2 2p^5\ ^2P - 2s2p^5 3p\ ^2D$	33·77

λ Plasma Focus Å	Intensity	λ Nearest Previous Observation or Calculation Å	Previous Assignment	Ion Stage for Present Assignment	Present Assignments (square brackets indicate less likely identifications i.e. weaker transitions)	λ Present Assignment Å
33·1	330	–	–	?	?	?
33·32	250	–	–	?	?	?
33·65	280	–	–	Ar XII	$2p^3\ ^2D-2p^23s^2S_{1/2}$ x	33·69
33·95	300	–	–	Ar XIII	$2p^2\ ^1S_0-2p3s^1P_1$	33·80
34·07	250	–	–	?	?	?
–	–	34·24	Ar XI $2p^{4\,3}P_2-2p^3(^2D)3d^3P$ ✓	Ar XI	$2p^4\ ^3P_2-2p^3(^2D)3d^3P$	34·34
34·35	480	34·35✓	Ar XI $2p^4\ ^3P_2-2p^3(^2D)3d^3D$ ✓	Ar XI	$2p^4\ ^3P_2-2p^3(^2D)3d^3D$	34·48
34·54	380	34·52✓	Ar XI $2p^4\ ^3P_{01}-2p^3(^2D)3d^3D$ ✓	Ar XI	$2p^4\ ^3P_0-2p^3(^2D)3d^3D$	34·52
34·80	350	34·79✓	Ar XII $2p^3\ ^4S_{3/2}-2p^23s^4P_{5/2}$ ✓	Ar XII	$2p^3\ ^4S_{3/2}-2p^23s^4P_{5/2}$	34·67
34·86	370	34·88✓	Ar XII $2p^3\ ^4S_{3/2}-2p^23s^4P_{1/2}$ ✓	Ar XII	$2p^3\ ^4S_{3/2}-2p^23s^4P_{1/2}$	34·76
35·39	380	35·39✓	Ar XI $2p^4\ ^3P_2-2p^3(^4S)3d^3D$ ✓	Ar XI	$2p^4\ ^3P_2-2p^33d^3D_{1,2,3}$	35·44
35·60	380	35·58✓	Ar XI $2p^4\ ^3P_{01}-2p^3(^4S)3d^3D$ ✓	Ar XI	$2p^4\ ^3P_{01}-2p^33d^3D_{1,2}$	35·70⊕
35·68	220	–	– –	Ar XII	$2p^3\ ^2D-2p^23s^2P_{1/2}$ x	35·62⊕
35·80	150	35·82✓+	Ar IX $2s^22p^6\ ^1S_0-2s2p^63p^1P_1$ +	Ar XII	$2p^3\ ^2P-2p^23s^2D$ x	35·72⊕
				(Ar IX	$2s^2\ 2p^6\ ^1S_0-2s2p^63p^1P_1$	35·95
36·10	300	–	– –	?	?	?
36·28	300	–	– –	Ar X	$2p^5\ ^2P_{3/2}-2p^43d^2D_{3/2}$	36·29
				([Ar XII	$2p^3\ ^2P-2p^2\ 3s^2P_{3/2}$ x	36·31]
36·52	300	36·55✓	unclassified Ar IX,X ?+	Ar X	$2p^5\ ^2P_{3/2}-2p^43d^2D_{3/2\ 5/2}$	36·54
				([Ar XII	$2p^3\ ^2P-2p^23s^2P_{1/2}$ x	36·50]
36·74	370	36·67✓	unclassified Ar IX,X ?+	?	?	?
36·93	150	36·98✓	unclassified Ar IX ?+	?	?	?
37·33	370	37·42✓+	Ar X $2p^5\ ^2P_{1/2}-2p^43d^2D_{5/2}$ +	Ar X	$2p^5\ ^2P_{3/2}-2p^43d^2D_{5/2}$	37·49
37·63	370	37·49✓+	Ar X $2p^5\ ^2P-2p^43d$? +	Ar X	$2p^5\ ^2P_{3/2}-2p^43d^2S_{1/2}$	37·61

λ Plasma Focus Å	Intensity	λ Nearest Previous Observation or Calculation	Previous Assignment	Ion Stage for Present Assignment	Present Assignments (square brackets indicate less likely identifications i.e. weaker transitions)	λ Present Assignment Å
38·16	250	38·22≁+	Ar X $2p^5\ ^2P_{3/2}-2p^4 3d^2D_{5/2}$ +	Ar X	$2p^5\ ^2P_{3/2}-2p^4 3d^2\ D_{5/2}$	38·24
38·33	380	38·40≁	unclassicied Ar X ?≁	Ar XI	$2p^4\ ^1D_2-2p^2 3s^1P_1$	38.43
B38·51	420	–	– –	Ar X	$2p^5\ ^2P_{1/2}-2p^4 3d^2D_{3/2}$	38·52
38·68	450	38·64≁	unclassified Ar X ?≁	Ar XI	$2p^4\ ^3P_2-2p^3 3s^3D$	38·62
38·8	390	38·88≁	unclassified≁	Ar XI	$2p^4\ ^3P_1-2p^3 3s^3D$	38.81
39·08	250	–	–	Ar XI	$2p^4\ ^3P_0-2p^3\ 3s^3\ D$	38.91
39·16	70	–	–	?	?	?
39·51	390	39·50≁	Ar XI $2p^4\ ^1D_2-2p^3 3s^1D_2$ ≁		$2p^4\ ^1D_2-2p^3 3s^1D_2$	39·45
39·75	350	39·74≁	Ar XI $2p^4\ ^3P_2-2p^3 3s^3S_1$ ≁		$2p^4\ ^3P_2-2p^3 3s^3S_1$	39.77
		39.82≁	unclassified Ar XI ?≁	Ar XI	$2p^4\ ^1S_0-2p^3\ 3s^1P_1$	39·94
39·98	330	39·95≁	Ar XI $2p^4\ ^3P_1-2p^3 3s\ ^3S_1$ ≁		$2p^4\ ^3P_1-2p^3 3s\ ^3S_1$	39·98
		40·02≁	Ar XI $2p^4\ ^3P_0-2p^3 3d^3S_1$		$2p^4\ ^3P_0-2p^3 3s\ ^3S_1$	40·03

* J.D. Garcia and J.E. Mack (1965).

≁ B.C. Fawcett, A.H. Gabriel, B.B. Jones and N.J. Peacock (1964)

\+ B.C. Fawcett (1965)

x In pure LS coupling there is no spin-orbit splitting in p^3 (Conlon and Shortley 1935)

⊕ HF wavelengths alone are not sufficiently accurate to distinguish between these lines; the order is suggested by intensities and isoelectronic extrapolations.

B in the 'Plasma Focus' column stands for blend.

O These two wavelengths coincide to within the numerical accuracy of the comparison between theory and experiment. The observed intensities are identical, and the assignments may therefore be interchanged.

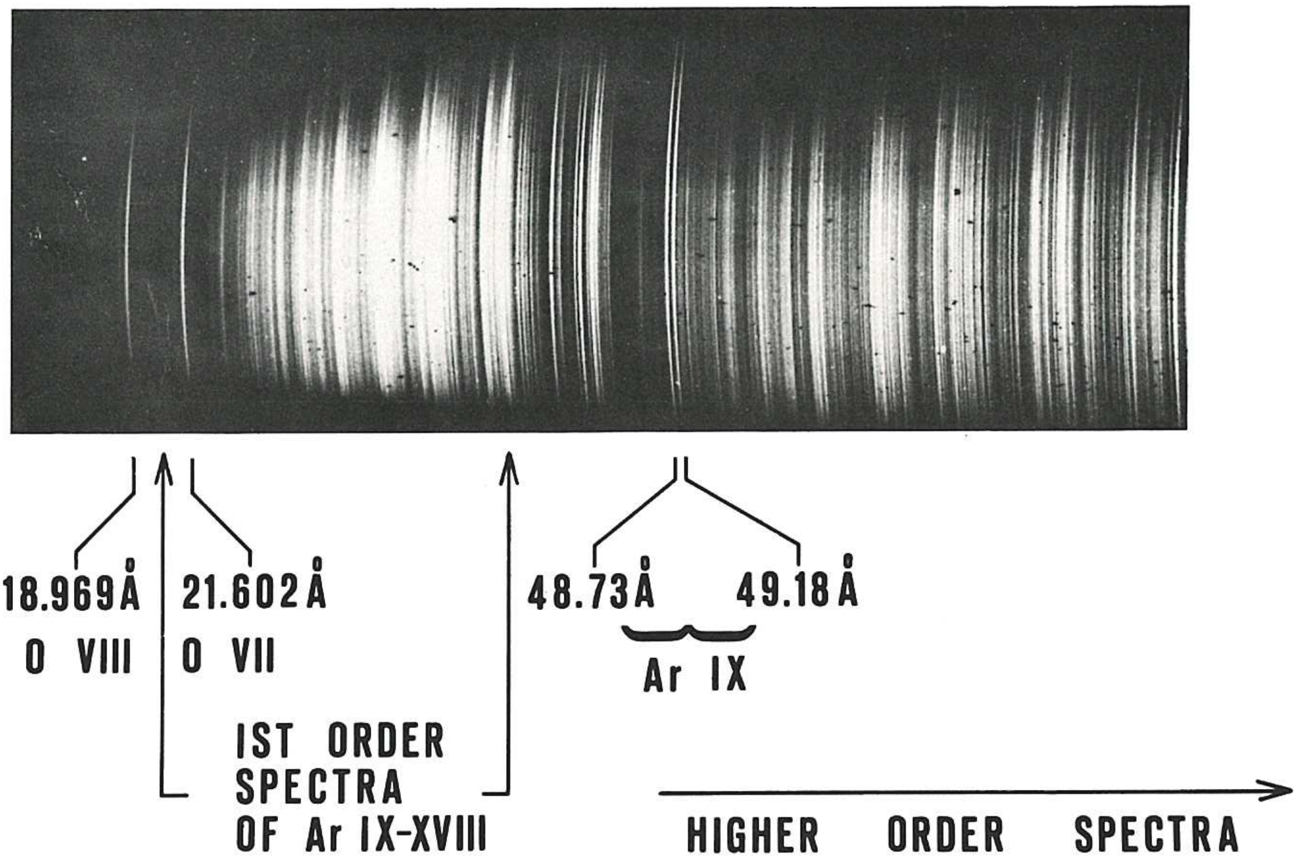

Fig. 1 Plasma focus argon spectrum