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EMISSION IN THE 50-80 Å REGION FROM HIGHLY IONIZED SILVER IN PLT TOKAMAK PLASMAS

By

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Emission in the 50-80 Å Region from Highly Ionized Silver in PLT Tokamak Plasmas

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ABSTRACT

The spectrum of silver emitted by Princeton Large Torus (PLT) tokamak plasmas has been recorded in the 25-150 Å region by a multichannel time-resolving grazing-incidence spectrometer. Silver atoms have been introduced in the tokamak plasma using the laser blow-off technique. For the first time, lines emitted within the 3p-3d transitions of Ag XXIX, Ag XXX, and Ag XXXI ions, between 50 and 80 Å, have been identified.

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INTRODUCTION

The spectra of highly ionized heavy elements have been studied extensively during the last few years mainly because of their importance in fusion experiments.[1-3] Recent experiments in the field of X-ray lasers also have pointed out the importance of knowing energy level structures of highly ionized heavy atoms.[4] Many energy levels within the excited $3s\,3p^{k+1}$ and $3p^{k-1}3d$ configurations of K I to Al I-like ions have been established for elements up to Z = 34.[5] For higher Z elements the situation is different: a very large number of lines emitted within the $3p^6 3d^k - 3p^5 3d^{k+1}$ transitions are superimposed on $3p^k - 3p^{k-1}3d$ lines emitted by several adjacent ionization states in a relatively narrow spectral region. This makes the identification of lines of various ionization states and their classification difficult; that is why the data concerning 3-3 transitions emitted by ions isoelectronic with Mn I to Si I are very scarce. A thorough discussion of the same transitions in zirconium and molybdenum can be found in a paper by Finkenthal et al.[6] In a very recent work, Wyart and the TFR Group studied the spectrum of krypton emitted from the TFR tokamak in several isoelectronic sequences from K I to O I in the soft X-rays.[7]

The present work discusses the identification and classification of lines belonging to K I, Ar I, and ClI-like Ag XXIX, Ag XXX, and Ag XXXI ions, emitted from the PLT tokamak plasma in the 50-80 Å region.

EXPERIMENT

The silver atoms under investigation were injected into the quasi-steady-state phase of the PLT tokamak discharge by the laser blow-off technique.[3] The central electron temperature was between 2 and 2.5 keV and the central electron density, 3×10^{13} cm^{-3}. The discharges were highly reproducible and the amounts of silver atoms introduced in the hydrogen plasma did not produce important perturbations in the space or time behavior of the major plasma parameters.[9]

The spectra have been recorded by means of a 2-m extreme-grazing-incidence spectrometer equipped with a Bausch and Lomb 600 1/mm grating, covering the 5-330 Å range.[10] The multichannel detector system consists of a 50-mm long, funneled, MgF_2-coated Galileo microchannel plate (MCP), associated with a phosphor screen and coupled by a flexible fiber optic conduit to a 1024-element Reticon photodiode array. The array is controlled and read out via an optical multichannel analyzer (OMA 1412F-1218, PAR, EG&G). The detector is interferometrically adjusted[11] and can be moved along the Rowland Circle. The instrument offers a simultaneous coverage of 20 Å at short wavelengths and 70 Å at the long wavelength extremity.

The spectral resolution in this experiment is 0.2 Å (FWHM); the measured wavelengths of unblended lines are accurate to 0.05 Å in the spectral range considered. The background radiation before the silver injection is very low, as can be seen in Fig. 1 (trace A): just after the injection (trace B) the background is due to the superposition of a very large number of lines originating from the 3-3 transitions mentioned above, emitted by 14 ionization states, from Co I- to Al I-like. Since the sensitivity curve of the spectrometer does not change noticeably over the narrow range considered, one can meaningfully compare intensities of lines emitted by various ionization states.

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RESULTS

The bright lines standing out over the dense line background are emitted by a few ions having a relatively simple term structure both in their ground and lowest excited configurations. Their sequence in the spectrum over a long period of time (each "frame" has been integrated over 80 ms), indicates that they belong to high ionization states. Indeed, previous work concerning the same transitions in zirconium and molybdenum using a much shorter time resolution (5.4 ms) indicated that ions having their emission peak between 1 and 2 keV will emit measureable signals for about 100 ms after the injection time.[6] The lines have been identified by comparison of the experimental data with extrapolated energy level values along the isoelectronic sequences, based on previous identifications of lines emitted by elements from titanium to molybdenum. The estimated error in the extrapolated values was in many cases about 0.5 Å; in the case of lines connecting two excited levels or lines originating from levels strongly affected by intercomplex configuration interaction, the error in the wavelength estimate could be as much as 1 Å. Relativistic, *ab initio* energy level and transition probability computations have also been performed, using the RELAC code,[12] for the Ag XXIX and Ag XXX ions belonging to the K I- and Ar I-like sequences, respectively. For the Cl I-like Ag XXXI ion, wavelengths and transition probabilities computed by Huang *et al.*[13] based on the multiconfigurational Dirac-Fock method, have been used in the classification. For convenience in the plasma diagnostics applications, the LS notation has been kept, in spite of the fact that for these high-Z ions an intermediate or even jj coupling description should be closer to the physical reality.

In the following, the results of the present work, summarized in Table I, are discussed briefly.

K I sequence

The ground term of Ag XXIX is $3p^63d\ ^2D$. The closest excited configuration above the ground is $3p^53d^2$. Several levels belonging to this configuration have J values higher than 7/2; this fact excludes many transitions to the ground. The remaining levels with J = 3/2, 5/2, and 7/2 give a large number of electric dipole lines between the two configuratons. Ab initio computations showed, however, that only six of them have weighted transition probabilities above 10^{12} sec^{-1}. Above Z = 30, only three lines emitted within the $3p^63d$ - $3p^53d^2$, $^2D_{3/2}$ - $^2D_{3/2}$, $^2D_{5/2}$ - $^2D_{5/2}$, and $^2D_{5/2}$ -$^2F_{7/2}$ transitions have been identified previously by Fawcett and Hayes[14] for Ge XIII and Ge XIV, Stratton et al.[5] for Ge XIV and Se XVI, Finkenthal et al.[6] for Zr XXII and Mo XXIV, and recently by Wyart et al.[7] for the two first transitions in Kr XVIII. The extrapolation for the $3p^53d^2$ $^2D_{3/2}$ level along the isoelectronic sequence was smooth, following very well the theoretical trend. In order to extrapolate the $3p^53d^2$ $^2D_{5/2}$ and $^2F_{7/2}$ energies, the split in the ground $3p^63d(^2D_{3/2}$ - $^2D_{5/2})$ is needed. Above the iron group, this split has been established experimentally only for Zr XXII and Mo XXIV[15] and recently for Ag XXIX.[16] For this reason, instead of extrapolating the energies of the levels, the wavelengths of the transitions have been considered.

Although the extrapolated values are estimated to be accurate only within about 0.5 Å, the line corresponding to the $^2D_{5/2}$ - $^2D_{5/2}$ transition has been identified easily because of its relative brightness. Indeed, as seen in Fig. 1, within one Å from the extrapolated value of 59.1 Å, it is the only strong line.

The $^2D_{3/2}$ - $^2D_{3/2}$ line has been predicted by extrapolation at 58.3 Å. Two bright lines are present in the spectrum at 57.73 Å and 58.13 Å. Using the experimental value of the energy for the $^2D_{5/2}$ - $^2D_{5/2}$ transition identified in the present work, together with ab initio RELAC calculations for the energy splits in both the ground and the excited ^2D terms, a wavelength of 57.64 Å has been predicted. Since the contribution of these splits to the whole transition energy is small, of about 2%, even an error of 15% in calculations will not lead to a discrepancy of more than 0.2 Å. In the case of Kr XVIII, comparison of calculated and observed split energies in Wyart's work[7] shows an agreement of about 3%. Consequently, the line observed at 57.73 Å was attributed to the $^2D_{3/2}$ - $^2D_{3/2}$ transition.

The other transitions expected to be strong, presented in Table I, were identified mainly by comparison with ab initio calculations. For the ^2D - ^2P lines, extrapolation from Krypton experimental data[7] compared with RELAC calculations was also used.

Ar I sequence

The $3p^6$ $^1S_0$ - $3p^5$ $3d$ $^1P_1$ line is expected to be the strongest emitted by Ag XXX amongst the $\Delta n = 0$ transitions. By extrapolating along the isoelectronic sequence, the line at 60.57 Å has been identified as emitted by this transition. As in the case of zirconium and molybdenum, it is one of the brightest lines in this spectral region. The $3p^6$ $^1S_0$ - $3p^5 3d$ $^3D_1$ line is expected to be about one order of magnitude less intense than ^1S - ^1P. It could not be found in the spectrum because of the combined effect of a not enough accurate wavelength prediction (the extrapolation had to be done from selenium because of lack of experimental data beyond Z = 34) and the relatively high background between 70-80 Å where the line is expected to appear.

Cl I sequence

The identifications in the Cl I isoelectronic sequence are mostly based on the comparison with the *ab initio* computations performed by Huang *et al.*[13] and previous indentifications for Zr XXIV and Mo XXVI by Finkenthal *et al.*[6] Above Z = 28 (Ni XII), only transitions originating from the two levels defined as $3p^4(^1D)3d\ ^2D$, following an earlier work performed by Fawcett,[17] have been identified for Ga [illegible] to Se XVIII by Fawcett and Hayes[14] and Stratton *et al.*[5] In the course of the analysis of zirconium and molybdenum spectra,[6] it became clear, however, that the assignment of the lines to various energy levels is quite complicated. First, the *ab initio* computations showed that the $3p^4(^1D)3d\ ^2D$ levels have very low transition probabilities (compared with $3p^4(^3P)3d\ ^2D$ and $3p^4(^1S)3d\ ^2D$), and most probably the observed lines in Refs. 14 and 5 should rather be assigned to the $3p^4(^3P)3d\ ^2D$ term. This seems to be confirmed by the comparison between the experimental energy levels previously identified as $(^1D)^2D$ and the computed $(^3P)^2D$, as shown in Figs. 2a and 2b, which indicates a very similar behavior along the isoelectronic sequence.

Another problem in the classification of the lines is the level crossing. Figure 2b presents one of the most prominent: the crossing between $(^1S)^2D_{5/2}$ and $(^3P)^2D_{5/2}$, occurring around Z = 39 (ζ = 23), as predicted by Huang calculations. This crossing is accompanied by a sudden inversion in the magnitude of the transition probabilities from the two levels involved toward the ground level $^2P_{3/2}$. For example, for Z = 38 (ζ = 22), the calculated A value is 6×10^{10} sec^{-1} for $(^1S)^2D_{5/2}$, compared to 3.4×10^{11} sec^{-1} for $(^3P)^2D_{5/2}$. On the other side of the crossing point, for Z = 41 (ζ = 25), the corresponding values are 4.7×10^{11} sec^{-1} and only 1.1×10^{10} sec^{-1}, respectively. Therefore, for low Z, $(^3P)^2D_{5/2}$ is the upper level giving rise to the intense line measured by Fawcett and Hayes[14] and by Stratton *et al.*,[5] while for Mo and Ag the correct designation of the corresponding line should be $^2P_{3/2}$ - $(^1S)^2D_{5/2}$. The line observed at 62.36 Å was assigned to this transition in Ag XXXI by comparison with calculated and extrapolated values. This identification is confirmed by the fact that it is the most intense line in the region around the predicted wavelength, as expected.

The other lines included in Table I were identified using predicted wavelengths obtained by extrapolation of previous data for lower Z and by comparison with the theoretical curves along the isoelectronic sequence, as shown in Fig. 2a. According to the theoretical computations, the level $(^1S)^2D_{3/2}$ is coming very close to $(^1D)^2S_{1/2}$ near $Z = 47$ ($\zeta = 31$), thus predicting the corresponding lines at practically the same wavelength (see Table I). However, the experimental data show a trend which indicates that the level $(^1S)^2D_{3/2}$ should pass above $(^1D)^2S_{1/2}$ already at $Z = 45$ ($\zeta = 29$). Therefore, the shorter observed wavelength at 62.81 Å was attributed to $^2P_{3/2}$ - $(^1S)^2D_{3/2}$, and the 63.28 Å line to the $^2P_{3/2}$ - $(^1D)^2S_{1/2}$ transition.

On the basis of extrapolation of lower Z experimental data, the line corresponding to the transition $^2P_{1/2}$ - (^3P) $^2D_{3/2}$ is expected to appear at about 65.0 Å, although a relatively large discrepancy remains with the _ab initio_ calculations of Huang. Such discrepancies appear also at lower Z. Two strong lines appear on the spectrum around the predicted wavelength, at 64.87 Å and 65.48 Å. However, the intensity of the transition under consideration is not expected to be so strong in tokamak plasmas, since the upper level has to be populated mainly by collisions from the ground state. The expected line is probably blended with the first of these two nonidentified lines that presumably belong to a higher ionization state (S I-like $3p^4$ - $3p^3$ 3d or P I-like $3p^3$ - $3p^2$ 3d transition).

Other possible transitions, namely those involving the $(^1D)\ F_{5/2}$ and $(^3P)^2F_{5/2}$ levels, which are predicted to appear in the 65-70 Å region, have theoretical transition probabilities of one order of magnitude lower. It is therefore difficult to separate these lines from the background.

CONCLUSIONS

Strong lines emitted in 3-3 transitions between the ground and the first excited configurations in Ag XXIX, Ag XXX, and Ag XXXI have been identified in the 50-80 Å region for the first time. The new identifications cover the gap between the relatively low states of ionization (Ni I-like) and higher ones (Mg I and Na I) previously studied for Ag. The lines identified in the present work fall in a spectral region where the very high line density makes the assignment of lines to given ionization states and their classification very difficult. The new results are useful for particle transport studies of high temperature tokamak plasmas and will help in further line identifications by isoelectronic extrapolation in even higher Z ions.

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Table 1 : Silver lines identified in the PLT spectrum between 50-70 Å.

Isoelectronic Sequence	Transition	Ion	λ(Å) calculated	λ(Å) predicted extrapol.	λ(Å) measured	$(2J+1)A_{ij}$ $10^{12}sec^{-1}$	$I_{meas.}$ (counts)
K I	$3p^6 3d-3p^5 3d^2$	AgXXIX					
	$^2D_{3/2}-^2D_{3/2}$		56.46*	58.3	57.73	5.1 a	460
	$^2D_{5/2}-^2P_{3/2}$		57.47	58.7	58.13	4.0	520
	$^2D_{5/2}-^2D_{5/2}$		57.81	59.1	59.06	7.0	840
	$^2D_{3/2}-^2P_{1/2}$		58.78	60.0	59.68	1.3	180
	$^2D_{5/2}-^2F_{7/2}$		59.93	61.5	61.95 T	4.3	340
	$^2D_{3/2}-^2F_{5/2}$		64.46		66.72 bl T	2.4	280
Ar I	$3p^6-3p^5 3d$	Ag XXX					
	$^1S_0-^1P_1$		60.08 a	60.9	60.57	2.6 a	1300
Cl I	$3p^5-3p^4 3d$	AgXXXI					
	$^2P_{3/2}-(^1D)^2P_{3/2}$		58.75 b	60.8	61.51 T	1.0 b	180
	" $-(^1S)^2D_{5/2}$*		60.21	62.7	62.36	3.6	1160
	" $-(^1S)^2D_{3/2}$		61.16	62.7	62.81	1.2	320
	" $-(^1D)^2S_{1/2}$		61.19	63.2	63.28	1.4	600
	$^2P_{1/2}-(^3P)^2D_{3/2}$		60.77	65.0	64.87 T bl?	2.2	800

Accuracy of measured wavelengths: ±0.05Å

I : Relative line intensity

A_{ij} : Spontaneous transition probability

*Designation for low Z elements: $(^3P)^2D_{5/2}$

a. Ab initio calculations, RELAC present work

b. Ab initio calculations of Huang et al (1983)

T : Tentative identification

bl : blended

FIGURE CAPTIONS

Fig. 1 Silver spectrum emitted from PLT tokamak in the 50-80 Å range.

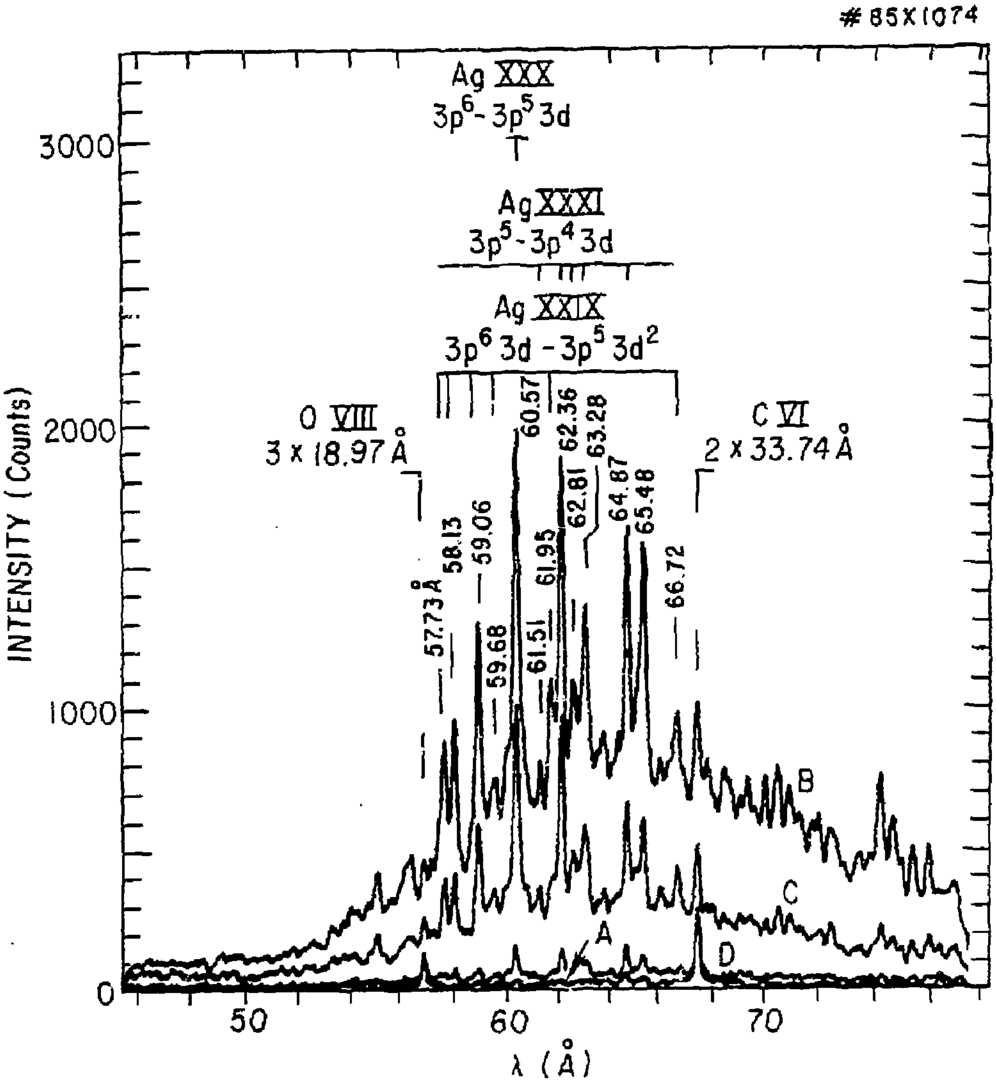
A. Before Ag injection $t = 400$ ms C. at $t = 560$ ms

B. After Ag injection $t = 480$ ms D. at $t = 640$ ms

Fig. 2 a - Reduced energy of the $(^3P)^2D_{3/2}$, $(^1D)^2S_{1/2}$ and $(^1S)^2D_{3/2}$ levels along the Cl I sequence.

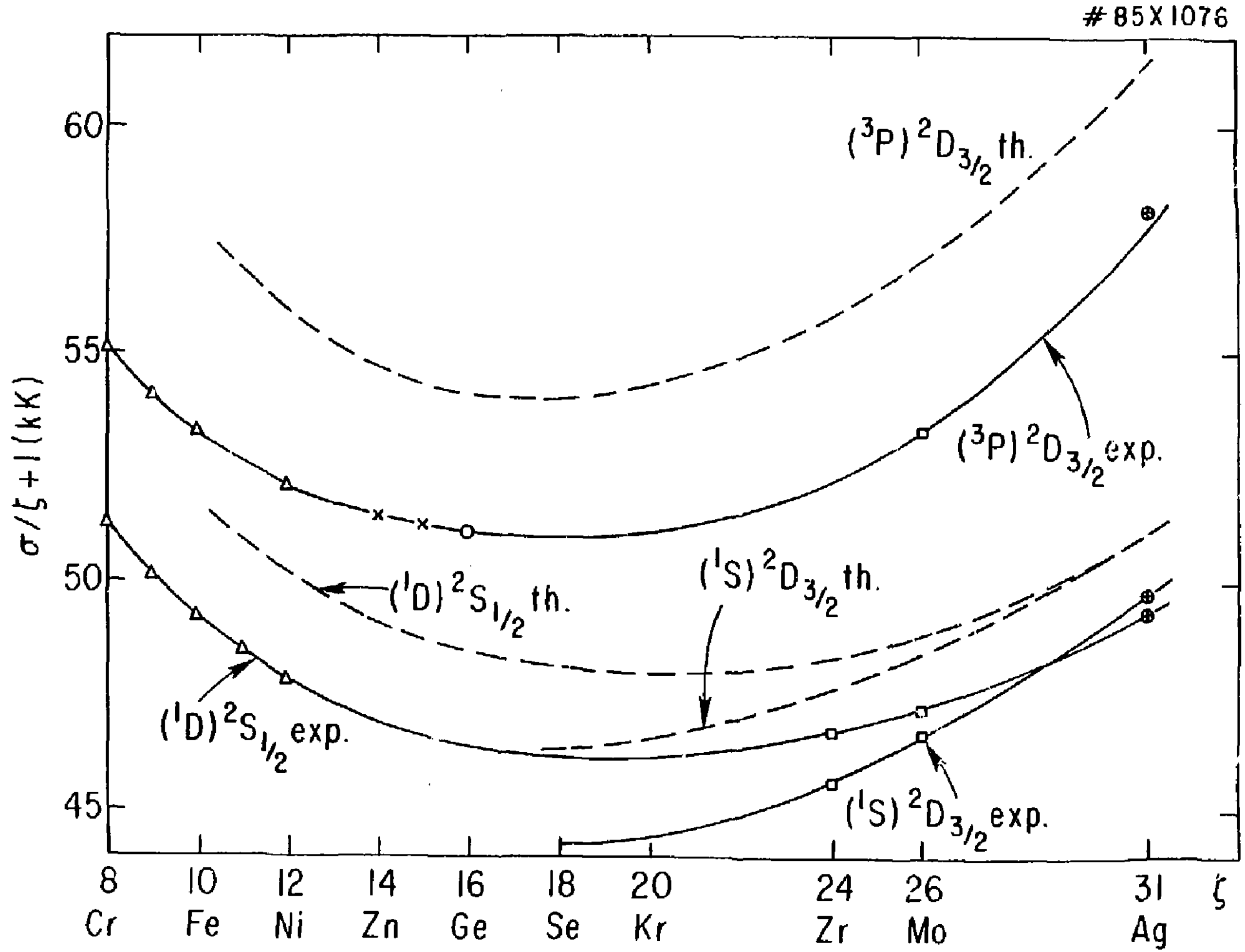
b - Reduced energy of the (^3P) and (^1S) $^2D_{5/2}$ levels along the Cl I sequence.

Experimental data:	-Δ-	Fawcett	(1971)
	-X-	Fawcett and Hayes	(1975)
	-O-	Stratton et al.	(1983)
	-□-	Finkenthal et al.	(1985)
	-⊕-	present work	
Theory:	--- / -·-	Huang et al.	(1983)



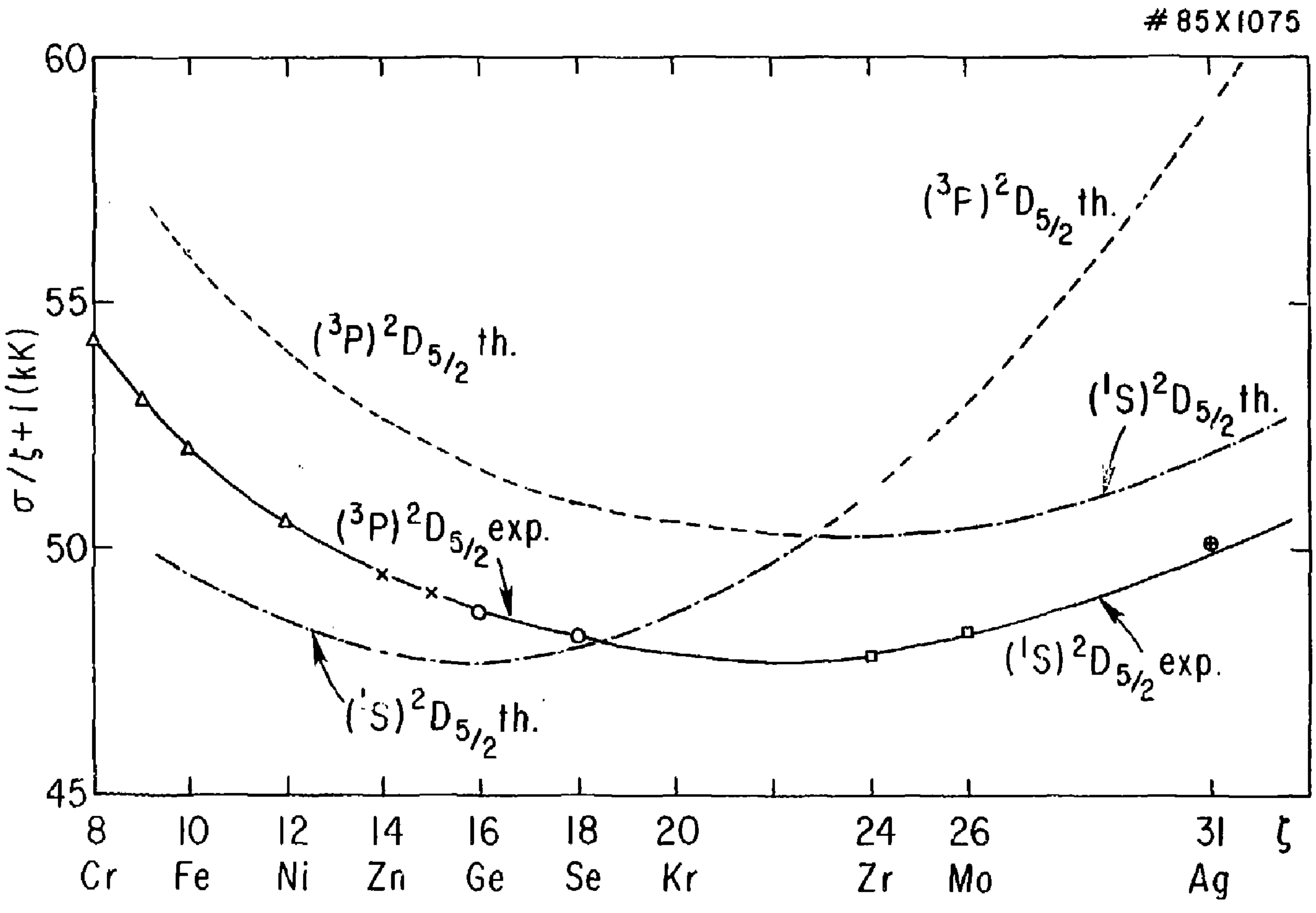
#85X1074
Ag XXX
3p6-3p5 3d
T
Ag XXXI
3p5-3p4 3d
Ag XXIX
3p6 3d - 3p5 3d2
O VIII
3 x 18.97 Å
C VI
2 x 33.74 Å
57.73 Å
58.13
59.06
59.68
60.57
61.51
61.95
62.36
62.81
63.28
64.87
65.48
66.72
A
B
C
D
INTENSITY (Counts)
0
1000
2000
3000
50
60
70
λ (Å)

Fig. 1



#85X1076
σ/ζ+1 (kK)
60
55
50
45
8 Cr
10 Fe
12 Ni
14 Zn
16 Ge
18 Se
20 Kr
24 Zr
26 Mo
31 Ag
ζ
(³P) ²D3/2 th.
(³P) ²D3/2 exp.
(¹D) ²S1/2 th.
(¹D) ²S1/2 exp.
(¹S) ²D3/2 th.
(¹S) ²D3/2 exp.

Fig. 2a



#85X1075
60
55
50
45
σ/ζ+1 (kK)
8
Cr
10
Fe
12
Ni
14
Zn
16
Ge
18
Se
20
Kr
24
Zr
26
Mo
31
Ag
ζ
(3P) 2D5/2 th.
(3F) 2D5/2 th.
(1S) 2D5/2 th.
(3P) 2D5/2 exp.
(1S) 2D5/2 exp.
(1S) 2D5/2 th.

Fig. 2b

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