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BEAM-FOIL STUDY OF AL II-VI BETWEEN 1100 AND 1900 Å

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Abstract. Beam-foil spectra of aluminium have been recorded between 1100 and 1900 Å. Lifetimes have been obtained for most of the 3p and 3d levels in Al IV, for many 3p, 3p' and 3d levels in Al V and for a few levels in Al II and Al III. Strong lines have been identified in Al VI; lifetimes have been measured for these transitions.

Résumé. Des spectres de l'aluminium ont été enregistrés entre 1100 et 1900 Å par spectroscopie faisceau-lame. Des durées de vie ont été mesurées pour la plupart des niveaux 3p et 3d de Al IV, pour beaucoup de niveaux 3p, 3p' et 3d de Al V et pour quelques niveaux de Al II et Al III. Des raies intenses dues à Al VI sont également présentes dans nos spectres; des durées de vie ont été obtenues à partir de ces transitions.

1. INTRODUCTION

Using the beam-foil technique we have studied Al II-VI in the wavelength region 1100-1900 Å. Previous beam-foil works on aluminium have been reported in refs. [1-8]. In this work, lifetimes have been measured for many levels in Al II-VI and have been calculated in Al V using the Scaled Thomas-Fermi method. We discuss also trends of oscillator strengths and lifetimes for selected transitions or levels along the Mg I and Ne I sequences.

The experimental arrangement has been described previously [8]. Al⁺ beams of about 1 μA were accelerated to energies ranging from 0.3 to 1.9 MeV. The length of ion beam viewed by our Seya-Namioka monochromator (equipped with a EMR 542G-08-18 photomultiplier tube) was about 0.2 mm.

2. RESULTS AND DISCUSSION

2.1 Spectra

Many lines of Al II-VI appear in our spectra. We have determined the charge-state of the emitting ions by studying the variation of intensity of the lines with the beam energy. In figure 1 we have plotted charge-state fractions as a function of energy for Al III-VII ions. The charge-state distributions have been measured at 286, 383 and 481 keV by Hvelplund et al. [9]. At higher energies, where to our knowledge no experimental data exist, we have calculated the distributions using the gaussian model [10] with values of the mean and standard deviation of the charge obtained by extrapolation of the low energy results [9]. We have also measured the intensity at the foil as a function of the beam energy for well identified lines in Al IV-VI and deduced relative beam-foil populations. These

values are also given in figure 1 for the 1557.3 Å, 1369.2 Å and 1320.6 Å transitions in Al IV, Al V and Al VI respectively.

Fig. 1- Charge-state fractions in carbon foils for Al ions determined as indicated in section 2.1 (full lines) and relative beam-foil populations at the foil for three well-identified transitions in Al IV, Al V and Al VI (dashed lines) as a function of the energy of Al ions.

The similar shapes of the two sets of curves (charge-state fractions and relative beam-foil populations) are clearly visible in figure 1 and have been obtained for all the transitions studied.

Classifications of transitions in Al II and Al III have been taken from Kelly and Palumbo [11]; in Al IV and Al V from Kaufman et al. [12] and

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Artru and Brillet [13] respectively. Very strong lines appear in our high energy spectra. The variation of intensity with the beam energy indicates that these lines are due to transitions in Al VI. Classifications of some of these lines have been proposed recently by Artru [14]. A section of an aluminium spectrum obtained at 1.9 MeV showing some Al VI lines is given in figure 2. The linewidth (FWHM) is about 0.7 Å.

Fig.2- A section of a beam-foil spectrum obtained using 1.9 MeV Al⁺ ions.

2.2 Lifetimes

Our results are presented in Table I. Each lifetime is the mean value of at least four repeated measurements. The quoted uncertainty represents plus or minus twice the standard deviation σ of the mean value (σ is estimated from the sample) and takes into account the error in the ion velocity. Decay data were analysed by the curve-fitting programme HOMER [15].

Al II and Al III.

Our lifetime results in Al II and Al III are compared with other experimental values when possible. In Table II, absorption oscillator strengths deduced from our lifetime values are compared to other experimental and theoretical results.

In Al II, our lifetime results are much longer than the beam-foil values of Berry et al. [3]. Our f -value for the $3p^3p^0-3p^2^3P$ transition ($\lambda_{\text{mult}}=1764.0$ Å) is smaller than the theoretical results.

However this situation is observed for all the recent experimental results for this transition in ions of the Mg I sequence as can be seen in figure 3. Our f -value for the $3p^3p^0-3d^3D$ ($\lambda_{\text{mult}}=1723.2$ Å) is in agreement with the value calculated by Zare [19].

Fig.3- Oscillator strengths versus $1/Z$ for the $3p^3p^0-3p^2^3P$ transition in the Mg I sequence. Theory: $\square$ ref. [25]; ∇ ref. [18]. Beam-foil results: $\blacktriangle$ this work; $\bullet$ other results: Mg I (ref. [26]), Si III and P IV (ref. [27]), S V (refs. [40,28]), Cl VI (refs. [29,30]), Ar VII (ref. [27]).

For the $3s^2^1S-3p^1p^0$ (λ 1670.8 Å) resonance transition, our f -value is significantly smaller than theoretical and experimental results. Several decay measurements for this line have been made at 300 and 500 keV and have given consistent results. A plot of the $3s^2^1S-3p^1p^0$ f -value along the Mg I sequence also seems to indicate that the experimental results are systematically lower than the theoretical values, at least for the heavier ions [31]. Although strong cascades are known to exist for λ 1764.0 Å (from $4s^3p^0$, 1934 Å [2]) and λ 1670.8 Å (from $3d^1D$, 1990 Å; $4s^1S$, 2816 Å [2]), they have not been observed in our decay curves. Therefore the true lifetimes could be masked by these cascades [32].

In Al III, the lifetime for the $3p^2p^0_{3/2}$ level has been obtained using the ANDC technique [33] taking into account repopulation from $3d^2D$ term (1612 Å). This value is 10 percent smaller than the lifetime obtained by the curve fitting programme and is in agreement with the theoretical results. The f -value trend for the $3s^2S-3p^2p^0$ transition along the Na I sequence has been discussed in detail by Crossley et al. [34] and will not

Table I - Lifetime results for Al II-VI

Ion	Wavelength	Transition	Lifetime of upper level(ns)		Cascade lifetimes (ns)	R ^a (%)	
			This work				Other exp.
			Exp.	Theory			
II	1763.87	3p ³ P ^o ₀ - 3p ² P ^o ₁	0.98±0.06		0.5±0.1 ³	~2	~0.5
	1763.95	3p ³ P ^o ₁ - 3p ² P ^o ₂					
	1760.10	3p ³ P ^o ₂ - 3p ² P ^o ₂					
	1724.97	3p ³ P ^o ₂ - 3d ³ D _{2,3}	0.97±0.06	0.77±0.1	0.65±0.1 ³ , 0.70±0.1 ¹⁶	~9	0.04
	1721.24	3p ³ P ^o ₂ - 3d ³ D _{1,3}	0.97±0.12				
	1721.27	3p ³ P ^o ₂ - 3d ³ D ₁	0.94±0.04				
	1670.79	3s ² S ₀ - 3p ¹ P ^o ₁	1.03±0.05			~9	0.10
					~10	~0.02	
III	1854.72	3s ² S _{1/2} - 3p ² P ^o _{3/2}	1.9±0.2		2.1±0.2 ³	~0.7, ~10	~2
	1384.13	3p ² P ^o _{3/2} - 4s ² S _{1/2}	0.64±0.06		-	~7	0.20
	1379.67	3p ² P ^o _{1/2} - 4s ² S _{1/2}	0.63±0.07		-	~8	0.14
	1352.83 ^b	3d ² D _{3/2} - 5f ² F _{5/2,7/2}	1.7±0.1		2.8±0.4 ^{2c}	~3, ~17	~2
IV	1639.05	3s ¹ P ^o ₀ - 3p ¹ D ₂	1.7±0.3			~0.4, ~5	1.9
	1589.28	3s ³ P ^o ₀ - 3p ³ D ₁	1.95±0.22			~0.4, ~10	~3
	1582.04	3s ³ P ^o ₀ - 3p ³ D ₂	1.92±0.14			~0.4, ~10	~3
	1557.25	3s ³ P ^o ₂ - 3p ³ D ₃	1.96±0.14			~0.5, ~10	~3
	1550.19	3s ³ P ^o ₂ - 3p ³ D ₃	1.8±0.3			~0.3, ~10	~3
	1584.46	3s ¹ P ^o ₁ - 3p ³ P ^o ₂	1.8±0.2			~0.4	~1.7
	1564.16	3s ¹ P ^o ₁ - 3p ³ P ^o ₂	1.80±0.06			~0.3	~1.5
	1494.79	3s ³ P ^o ₂ - 3p ³ P ^o ₁	2.09±0.07			~0.3	~1.5
	1457.96	3s ³ P ^o ₂ - 3p ³ P ^o ₁	1.78±0.08			~0.3	~0.7
	1441.83	3s ³ P ^o ₂ - 3p ³ P ^o ₁	1.65±0.24			~0.4, ~5	~0.5
	1404.75	3s ³ P ^o ₂ - 3p ³ P ^o ₂	1.65±0.16			~0.6, ~5	~1
	1388.79	3s ³ P ^o ₂ - 3p ³ P ^o ₁	1.76±0.08			~0.3	~1
	1447.51	3s ³ P ^o ₂ - 3p ³ D ₂	1.6±0.2			~0.5, ~5	1.3
	1402.78	3p ³ P ^o ₀ - 3d ³ P ^o ₂	0.68±0.08			~5	~0.06
	1376.62	3p ³ P ^o ₂ - 3d ³ P ^o ₂	0.72±0.06			~6	0.07
	1337.90	3p ¹ D ₂ - 3d ³ P ^o ₂	0.68±0.04			~5	0.07
	1264.18	3p ³ P ^o ₁ - 3d ³ D ^o ₂	0.68±0.04			~9	0.05
	1257.62	3p ³ P ^o ₂ - 3d ³ D ^o ₂	0.63±0.05			~5	0.07
	1248.79	3p ¹ P ^o ₁ - 3d ³ D ^o ₂	0.65±0.03			~7	0.06
	1220.55	3p ³ D ₂ - 3d ³ P ^o ₂	0.61±0.06			~6	0.08
	1240.86	3p ³ D ₂ - 3d ³ P ^o ₂	0.64±0.07			~5	0.05
	1240.21	3p ³ D ₁ - 3d ³ P ^o ₂					
	1237.19	3p ³ D ₃ - 3d ³ P ^o ₄	0.76±0.04			~9	0.04
V	1539.12	3s ⁴ P _{3/2} - 3p ⁴ P ^o _{1/2}	2.0±0.4	1.8		~0.5, ~10	~3
	1526.14	3s ⁴ P _{5/2} - 3p ⁴ P ^o _{3/2}	2.10±0.17	1.8		~0.5, ~10	3.5
	1475.64	3s ² P _{3/2} - 3p ² D ^o _{5/2}	1.73±0.06	1.5		~0.6, ~20	~3
	1455.27	3s ² D _{3/2} - 3p ² F ^o _{5/2}	1.82±0.16	1.5		~0.5	~1.7
	1454.65	3s ² D _{5/2} - 3p ² F ^o _{5/2}					
	1445.87	3s ² D _{5/2} - 3p ² F ^o _{7/2}	1.91±0.17	1.5		~0.4	~1.7
	1375.79	3s ² P _{3/2} - 3p ² F ^o _{7/2}	0.97±0.09	-		~8	0.07
	1373.70	3s ⁴ P _{1/2} - 3p ⁴ D ^o _{3/2}	1.31±0.09	1.3		~0.1, ~20	~3
	1369.20	3s ⁴ P _{3/2} - 3p ⁴ D ^o _{5/2}	1.55±0.14	1.2		~0.4, ~10	~3
	1352.87	3s ⁴ P _{5/2} - 3p ⁴ D ^o _{7/2}	1.53±0.09	1.2		~0.4	3
	1350.52	3s ⁴ P _{3/2} - 3p ⁴ D ^o _{5/2}	1.46±0.12	1.3		~0.3, ~4	~2
	1288.23	3s ² D _{3/2} - 3p ² D ^o _{3/2}	1.43±0.07	1.0		~0.3	~1
	1287.70	3s ² D _{5/2} - 3p ² D ^o _{5/2}					
	1195.37	3s ⁴ P _{3/2} - 3p ⁴ S ^o _{3/2}	0.99±0.08	0.8		~0.1	~1.5
	1165.42	3s ⁴ P _{5/2} - 3p ⁴ S ^o _{3/2}	1.09±0.10	0.8		~0.2	~2
	1168.48	3p ⁴ S ^o _{3/2} - 3d ⁴ F ^o _{5/2}	0.47±0.06	-		~5	~0.1
1088.67	3p ⁴ D ^o _{5/2} - 3d ⁴ F ^o _{9/2}	0.70±0.03	-		~10	0.03	
1088.52	3p ⁴ D ^o _{3/2} - 3d ⁴ F ^o _{9/2}						
VI	1331.19	3s ⁵ S ₀ - 3p ⁵ P ₁	1.66±0.17			~0.4, ~10	~3
	1327.67	3s ⁵ S ₀ - 3p ⁵ P ₂	1.68±0.09			~0.5, ~10	~4
	1321.57	3s ⁵ S ₀ - 3p ⁵ P ₃	1.71±0.14			~0.5, ~10	~4
	1324.91	3s ³ D ^o _{3/2} - 3p ³ F ₃	1.78±0.11			~0.4, ~10	~3
	1320.57	3s ³ D ^o _{3/2} - 3p ³ F ₄	1.78±0.10			~0.4, ~10	~4

a) replenishment ratio at the foil; b) measured at 300 keV to avoid blend with Al V; c) measured through another transition.

Table II - Oscillator strengths in Al II and Al III

Ion	Multiplet Wavelength (Å)	Absorption oscillator strength		
		This work	Other exp.	Theory
II	1764.0	0.48±0.03	0.94 ³	0.61 ¹⁷ , 0.586 ¹⁸
	1723.2	0.78±0.04	0.96 ³	0.90 ¹⁷ , 0.81 ¹⁹
	1670.8	1.26±0.06	1.9 ³ , 1.80 ¹⁶	1.84 ¹⁷ , 1.75 ¹⁹ , 2.11 ²⁰ , 1.77 ¹⁸
III	1857.4	0.81±0.08	0.75 ³	0.90 ²⁰ , 0.831 ²¹ , 0.873 ²² , 0.836 ²⁴ , 0.60 ²³
	1382.7	0.15±0.02	-	0.122 ²¹ , 0.129 ²² , 0.119 ²³ , 0.131 ²⁴

be repeated here. Our lifetime result (1.7 ns) for the $5f\ 2F^o$ term is in agreement with the theoretical values of Lindgard and Nielsen [21] (1.58 ns) and Biémont [22] (1.61 ns). For $\lambda_{\text{mult}} = 1382.7\text{ \AA}$ our f -value is in agreement with the theoretical results.

Al IV and Al V.

In Table I we also present our lifetime results for most of the 3p and 3d levels in Al IV and for many 3p, 3p' and 3d levels in Al V.

In Al IV, we have studied the lifetime trends for some levels along the Ne I sequence. The experimental results appear to be slightly but systematically longer than the calculated values. As an example, we show in figure 4 the behaviour of the lifetime for the $3p\ ^1D_2$ level along the Ne I sequence. The curves in dashed and full lines represent the experimental and theoretical trends respectively.

Fig.4- Lifetime trend along the Ne I sequence for the $3p\ ^1D_2$ level. Theoretical values : refs. [35,37,38]. Experimental results : refs. [36,38-41].

In Al V, our experimental lifetimes have been compared with theoretical values computed by the Scaled Thomas-Fermi method using mixing coefficients taken from ref. [13]. As for Al IV, the experimental results are slightly longer than the calculated lifetimes.

Al VI.

A few unidentified lines appearing in our spectra were attributed to Al VI owing to their variation of intensity with the beam energy (see section 2.1). These lines were observed independently by Artru [14] using a triggered-spark source. In Table I we give our lifetime results for five Al VI lines classified by this author.

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