Beam-Foil Studies of Multiply Ionized Oxygen

B. Denne, L. Engström, S. Huldt, J. O. Ekberg, L. J. Curtis, K. Ishii,[1] E. Veje[2] and I. Martinson

Department of Physics, University of Lund, 2-223 62 Lund, Sweden

Abstract

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Beam-foil spectra of oxygen have been recorded in the region 2000–4500 Å with emphasis on good spectral resolution. Wavelengths for many hydrogenic transitions in O VI–O VII have been determined with ± 0.1–0.5 Å uncertainties. The data are compared with predictions using polarization formulae. A few lifetimes are also reported.

1. Introduction

In this paper we present the results of a beam-foil study of wavelengths and lifetimes in multiply ionized oxygen. Of the spectra O IV–O VIII considered here only those of O IV and O V have been thoroughly investigated earlier, by Bromander [1] and by Bockasten and Johansson [2], respectively. In the far UV region, additional material for these spectra has more recently been given by Edlén [3]. The compilation by Moore [4] shows that information about energy levels is less complete for O VI and O VII where only low-lying levels are accurately known. Neither does there exist much experimental material for O VIII, but in this spectrum all energy levels can be computed to very high accuracy [5]. Thus, with the exception of the study of Bockasten et al. [6] who observed some hydrogenic lines in O VI in the range 2000–6000 Å, most investigations of O VI and O VII examined only the extreme UV region.

However, there are several beam-foil studies of the high-lying part of the O VI–O VIII level schemes. In an early experiment Bashkin et al. [7] observed the region 2700–6600 Å using beam energies of 1 and 2 MeV. A large number of oxygen lines were observed, many of which could not be classified at that time. Subsequently Lewis et al. [8] determined lifetimes for many excited levels in O II–O VI. Several new oxygen transitions also appeared in their experiment. Some of the unidentified line [6, 7] were later ascribed to transitions between hydrogen-like levels in highly ionized oxygen [9]. In 1970 the Lyon group observed hydrogen-like transitions in O V–O VII [10–12] using 2 MeV ions from a Van de Graaff accelerator and 18 MeV beams from the Orsay linear accelerator. Energies up to 36 MeV were used by Hallin et al. [13] who observed more than 30 hydrogen-like transitions belonging to the spectra O V–O VIII. Buchet et al. [14] have continued the work described in [10], and additional results for O VII are now available.

The beam-foil method is very efficient for populating states with high n and l quantum numbers in multiply ionized atoms. The mechanism is assumed to be electron capture at the exit

¹ Department of Engineering Science, Kyoto University, Kyoto 606, Japan.
² H. C. Ørsted Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark.

side of the foil [15]. Because of the low particle density and absence of interionic fields the high n, l states do not undergo Stark quenching or collisional de-excitation (as in many other light sources) but decay by radiative processes.

Unfortunately the spectral resolution and the wavelength accuracy were not very high in most of the previous beam-foil studies of multiply ionized oxygen. The hydrogenic lines have been reported with wavelength uncertainties of up to ± 2 or ± 3 Å. One of the goals of the present paper was to determine the wavelengths more accurately. In addition to spectral studies we also made lifetime measurements for a few selected levels.

2. Experiment

Oxygen beams were obtained from the 3 MV Pelletron tandem accelerator at the University of Lund. We used beam energies of 2, 4.5, 6 and 9 MeV for spectral scans. For each of these energies a spectrum between 2000 and 4500 Å was registered with a McPherson Model 2051 1 m grating monochromator, equipped with a liquid nitrogen cooled EMI 9789 photomultiplier. To obtain satisfactory wavelength resolution we refocussed the monochromator for a moving light source [16]. Linewidths of 1.5–2 Å were achieved in this way. The data were registered with an automated on-line system specially constructed for beam-foil measurements. Details about the experimental method can be obtained in [17, 18]. The spectra were recorded with a Calcomp 565 digital plotter and were also stored on hard copy as well as on floppy discs. For a first analysis the spectra were compared with previous information [1–4] on multiply ionized oxygen. A peak finding program was used to calculate the final wavelength values for all peaks in the spectrum. Selected strong and well isolated oxygen lines in our spectra were here used as references.

3. Results

3.1. Wavelengths

In Fig. 1 we show part of the spectrum, obtained at 4 MeV. Our spectra (2000–4500 Å) contain more than 200 well resolved oxygen lines. The line density is highest at 2 MeV where many O III lines are still quite prominent. At higher energies O III transitions became weak or disappeared. The O III spectrum is incompletely known, but since work is presently in progress [19] we made no effort to contribute here, concentrating instead on higher degrees of ionization, for which we have found a number of new transitions.

For a non-penetrating orbit, the energy $E(n, l, Z)$ can be described by the polarization formula [20]

$$E(n, l, Z) = E_0(Z) - T_H(n, l, Z) - \Delta_p(n, l, Z) \qquad (1)$$

where E_0 is the ionization potential and T_H is the hydrogenic term value. The polarization energy Δ_p can be expressed as
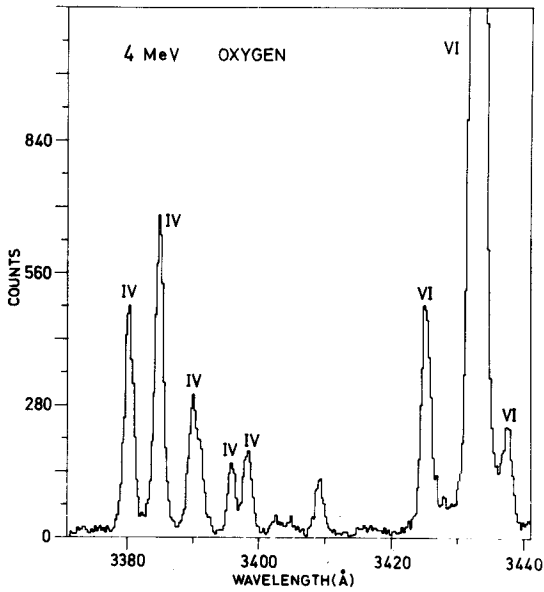
Fig. 1. Part of an oxygen spectrum, obtained with 4 MeV ions.

$$\Delta_p(n, l, Z) = A(Z)P(n, l)[1 + k(Z)q(n, l)] \qquad (2)$$

Here $A(Z)$ and $k(Z)$ are constants which involve the dipole and quadrupole polarizabilities of the core whereas $P(n, l)$ and $q(n, l)$

are functions tabulated in [20]. For transitions between two non-penetrating orbits the wavelength is independent of $E_0(Z)$ and can be predicted from $A(Z)$ and $k(Z)$ alone. If they can be connected to the ground state through known combinations, then these non-penetrating transitions can provide a value for the ionization potential.

3.1.1. *O IV.* This spectrum has been analyzed by Bromander [1]. Later Edlén [3] published additional information about high-lying configurations. At our lowest energy, 2 MeV, O IV transitions were quite prominent and our spectra exhibited most of the lines in the region 2000–4500 Å listed by Bromander. In addition we observed a new line at 2895.2 ± 0.3 Å which is ascribed to the $5g\,^2G$–$7h\,^2H$ transition. (See Table I). Both these terms are known and the calculated value is 2895.39 Å, using the energies in [1]. To search for additional hydrogenic lines we have recalculated the hydrogenic part of the O IV spectrum using the values $A(Z) = 205$ and $k(Z) = 58.7$. These constants were computed from the values $A = 2.249 \times 10^7 \text{ cm}^{-1}$ and $B = 1.321 \times 10^9 \text{ cm}^{-1}$ given by Bromander [1] who used Bockasten's [21] version of the polarization formula. Many lines that should be strong in beam-foil spectra, lie unfortunately outside our wavelength range.

3.1.2. *O V.* In this spectrum the hydrogen-like levels up to 8 k are known [2]. We observed most of the expected O V lines

Table I. *Hydrogen-like transitions in multiply ionized oxygen*

Spectrum	Measured wavelength (Å)		Transition	Calculated wavelength (Å)
	This work	Other experiments[b]		
O IV	2895.2 ± 0.2[a]		$5g\,^2G$–$7h\,^2H$	2895.39
O V	2993.1 ± 0.2	2993.0[c]	$6h\,H$–$8i\,I$	2992.47
O VI	2066.1 ± 0.3		$5d$–$6f$	2065.65
	2070.0 ± 0.2	$\begin{cases} 2069.92^d \\ 2070.29^d \end{cases}$	$\begin{cases} 5f\text{–}6g \\ 5g\text{–}6h \end{cases}$	2069.94 2070.30
	2082.1 ± 0.2	2082.18[d]	$\begin{cases} 6f\text{–}8g \\ 6g\text{–}8h \\ 6h\text{–}8i \end{cases}$	2081.93 2082.17 2082.24
	2430.8 ± 0.3		$\begin{cases} 7h\text{–}10i \\ 7i\text{–}10k \end{cases}$	2431.30 2431.34
	3138.6 ± 0.2		$\begin{cases} 7g\text{–}9h \\ 7h\text{–}9i \\ 7i\text{–}9k \end{cases}$	3138.58 3138.69 3138.74
	3425.9 ± 0.1		$6d$–$7f$	3425.93
	3433.6 ± 0.2	3433.69[d]	$\begin{cases} 6f\text{–}7g \\ 6g\text{–}7h \\ 6h\text{–}7i \end{cases}$	3433.59 3422.59 3433.76
	3438.2 ± 0.2		$6f$–$7d$	3438.38
	4500.1 ± 0.7		8–10	4498.97
O VII	2305.7 ± 0.2		$\begin{cases} 7g\text{–}9h \\ 7h\text{–}9i \\ 7i\text{–}9k \end{cases}$	2305.84 2305.92 2305.96
	2522.7 ± 0.2		$\begin{cases} 6f\text{–}7g \\ 6g\text{–}7h \\ 6h\text{–}7i \end{cases}$	2522.25 2522.58 2522.71
	2525.5 ± 0.4		8–11	2525.88
	3304.7 ± 0.5		8–10	3305.25
	3887.0 ± 0.3		$\begin{cases} 7g\text{–}8h \\ 7h\text{–}8i \\ 7i\text{–}8k \end{cases}$	3886.68 3886.87 3886.97

[a] The wavelengths are weighted mean values from several spectral scans. The uncertainties were estimated from the differences between our computer-fitted data and previously known wavelengths for other O multiplets.

[b] Only high-resolution data are included here.

[c] Bockasten and Johansson [2].

[d] Bockasten et al. [6].

in our spectra. For example, the $2s6h$–$2s8i$ transition appeared rather strong in our spectra at 2993.1 ± 0.2 Å. This line is quite weak in spark spectra.

Here, also, we have recalculated the hydrogenic part using $A(Z) = 663$ and $k(Z) = 53.1$ which are equivalent to the values $A = 72.7 \times 10^6$ cm^{-1} and $B = 3.86 \times 10^9$ cm^{-1} given in [2]. With the possible exception of the 2993 Å line the hydrogenic lines in O V should be more accurately determined in [2] than in our work and therefore we will not list our wavelengths.

3.1.3. O VI. In the O VI spectrum, Bockasten et al. [6] classified five hydrogen-like transitions. In a recent analysis of the Li I isoelectronic sequence, Edlén [22] recommends the values $A(Z) = 3.4112$ and $k(Z) = 3.6725$ for O VI. We have calculated the term values of hydrogenic levels in O VI using these constants. The results are compared with our experimental values in Table I. Several new O VI transitions were measured in this work. For example, as seen in Fig. 1, we observed the $6d$–$7f$ and $6f$–$7d$ transitions in O VI which were well resolved from the strong $6gh$–$7ghi$ transition.

The region around 3430 Å was scanned with 0.1 Å steps. Using the value 3433.69 Å for the $6gh$–$7ghi$ complex [6] we obtain the wavelengths 3425.9 ± 0.1 Å and 3438.2 ± 0.2 Å for the $6d$–$7f$ and $6f$–$7d$ transitions respectively. These wavelengths are therefore more accurately determined than most others measured in this work. The agreement with the polarization formula as well as with previous experimental data [6] is excellent.

3.1.4. O VII. In this spectrum a number of hydrogenic transitions were reported in [10–14], but it is difficult to estimate the experimental wavelength uncertainties in those studies.

For a one-electron core with no penetration the electric dipole and quadrupole polarizabilities can be accurately computed [23]. The polarization constants can be expressed as

$$A(Z) = \frac{9}{2}\left(\frac{Z-1}{Z}\right)^2 \tag{3}$$

$$k(Z) = \frac{10}{2}\left(\frac{Z-1}{Z}\right)^2 \tag{4}$$

Thus eqs. (1) and (2) relate each non-penetrating energy level $E(n, l, Z)$ in a helium-like system to the ionization potential $E_0(Z)$ with no additional parameters. We therefore combined our measured wavelengths of non-penetrating transitions in O VII with those of Bucket et al. [14], and connected to the ground state via the known $1s3d$ term values, using the effective value

$$E(1s3d) \equiv [E(1s3d\,^3D_2) + E(1s3d\,^1D_2)]/2 \tag{5}$$

In this manner we obtained estimates of varying accuracy for the $3d$, $4d$, $5d$, $6d$, $4f$, $5g$, $6g$, $7g$, $8g$, $9i$ and $9h$ energy levels, with each inferring a value for E_0. Combining all values by a weighted average, we obtained the ionization energy

$$E_0(\text{O VII}) = 5\,962\,790 \pm 120\ \text{cm}^{-1}$$

This result agrees with the published value $5\,962\,800 \pm 300$ cm^{-1}, [4], but reduces the uncertainty somewhat. If we instead combine the experimental energy of the $1s3d\,^1D$ term, $5\,365\,470$ cm^{-1}, (based on measurements of Svensson [24] and Cantú et al. [25]) with Brown's [26] calculated $3d$–$4f$ transition wavelengths and then apply eqs. (3) and (4) for the $4f^{1,3}F$ levels we obtain the value $5\,962\,930 \pm 180$ cm^{-1}, which also agrees with our new result. The very accurate variational calculations of Accad et al. [27] yield an ionization energy of $5\,963\,517.6$ cm^{-1}. Here the Lamb shift correction is not included, however. Comparison between accurate theoretical and experimental ionization energies for the He-like ions gives interesting information about the $1s^2$ Lamb shift [28, 29]. We are therefore extending the present work on the VUV with the aim of reducing the experimental errors.

3.2. Lifetimes

We measured the lifetimes for the $3p\,^2P_{1/2}$ and $3p\,^2P_{3/2}$ levels in O IV, the $6h\,H$ levels in O V and $7f\,^2F$ level in O VI. It would have been possible to determine many more lifetimes but there is already a great deal of information available [30] and extensive efforts are motivated only if the accuracy can be increased substantially. All our lifetime data were taken at several energies so as to minimize possible systematic uncertainties (energy loss problems, blends from weak lines etc.). Our lifetime results are given in Table II.

Our results for the $3p\,^2P_{1/2}$ and $3p\,^2P_{3/2}$ levels are practically identical, as expected from *LS*-coupling. The values obtained agree with previous data [8, 11, 31]. No theoretical lifetimes are available for the $3p\,^2P$ term. The $3s\,^2S$–$3p\,^2P$ transition probability has been calculated by Kelly [32], and by Lindgård [33] who found a value of 1.48×10^8 s^{-1} which would thus correspond to a lifetime of 6.8 ns. However, the $3p\,^2P$ term also decays to the low-lying $2p^2\,^2S$, ^2P and ^2D terms and our result shows that these branches in the UV have a significant transition probability.

The decay of the O V line at 2941 Å ($5g$–$6h$) has ealier been investigated by Lewis et al. [8] and Druetta et al. [34] with different results. We therefore remeasured this lifetime using high

Table II. *Lifetimes for levels in multiply ionized oxygen*

			Lifetime of upper level (ns)		
Spectrum	Upper level	Wavelength (Å)	This work	Other experiments	Theory
O IV	$3p\,^2P_{3/2}$	3063	1.53 ± 0.04	1.63[a]; 1.53[b]; 1.5[c]	
	$3p\,^2P_{1/2}$	3073	1.53 ± 0.04	1.53[a]; 1.53[b]	
O V	$6h\,H$	2941	1.0 ± 0.1	1.85[a]; 0.9[d]	0.82[d]
O VI	$7f\,^2F$	3426	0.31 ± 0.02		0.291[e]

[a] Lewis et al. [8].
[b] Druetta et al. [31].
[c] Ceyzeriat et al. [11]
[d] Druetta et al. [34].
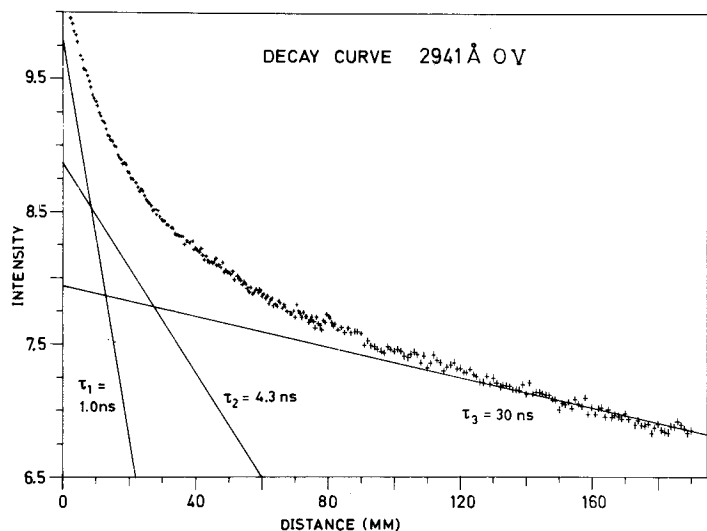[e] Lindgård and Nielsen [35].

Fig. 2. Decay curve for the 2941 Å line in O V (*5g–6h*). The intensity scale is in natural logarithm units. The statistical error for each point is indicated.

counting statistics and good spatial resolution. One of our decay curves is shown in Fig. 2. It is obvious that this curve (like many other decay curves for high n, l states in multiply ionized atoms) is of a complex character. Because of the favourable statistics and negligible background we were able to make reproducible decompositions into three exponentials, the steepest of which gives a *6h H* lifetime of 1.0 ns, in excellent agreement with the measurement of Druetta et al. [34]. Those authors also made a Coulomb-approximation calculation of the *6h H* lifetime which agrees well with experimental data.

We finally determined the $7f\,^2F$ lifetime in O VI from the *6d–7f* (3426 Å) line, classified in this work. Table II shows that our value is in excellent agreement with the Coulomb-approximation calculations of Lindgård and Nielsen [35].

4. Summary

We have given comparatively accurate wavelengths for several hydrogenic lines in multiply ionized oxygen. The data confirm previous estimates of dipole and quadrupole polarizabilities. The present wavelength uncertainties can be reduced by concentrating on smaller wavelength regions and increasing the number of data points for each line. Such work, also to be extended toward shorter wavelengths, is therefore being initiated.

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