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Radiative Lifetimes of Excited Electronic States in Ionic-Species of Oxygen

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The beam-foil technique has been used to measure lifetimes of excited electronic states in oxygen II through VI. The possibility of cascading from above affecting the measurements is discussed. Only the most intense multiplets and members thereof were observed in the range between 2000 and 5000 Å. Where it is possible the lifetimes and some transition probabilities that may be extracted are compared with available calculations. A considerable number of transitions were untabulated and were identified through the use of a computer program.

I. INTRODUCTION

Research in plasmas and astrophysics is highly dependent on the oscillator strengths of radiative transitions from excited electronic states of neutral and ionic species of atoms. The absorption oscillator strengths, f_{ij}, are related to the radiative lifetimes, τ, of such states through the transition probability for spontaneous emission, A_{ij}:

$$A_{ij} = (8\pi^2 r_0 c g_i / g_j \lambda_{ij}^2) f_{ji} , \quad (1)$$

$$\tau_i = (\textstyle\sum_j A_{ij})^{-1} , \quad (2)$$

$$\tau_i = (8\pi^2 r_0 c g_i \textstyle\sum_j f_{ji} / g_j \lambda_{ij}^2)^{-1} , \quad (3)$$

where g is the statistical weight of the appropriate state and r_0, c, and λ are the classical electron radius, the velocity of light, and the wavelength of the transition, respectively. The beam-foil technique[1–4] has become a useful and quite productive method for the determination of radiative lifetimes and, when used in conjunction with other techniques, yields values for transition probabilities.

The beam-foil technique used in this determination of radiative lifetimes of oxygen has been described in detail previously[4] (applied to measurements in nitrogen) but is summarized briefly here. A high-velocity beam of singly charged ions from an accelerator is directed through a thin, freely supported foil of carbon (~ 1000 Å thick). The ions emerge from the foil in a variety of ionic species in a state of electronic excitation because of charge-loss interactions. The process of spontaneous decay from these states as the ions move along gives rise to optical radiation with intensity a function of distance from the foil. Observation of this decay of intensity of a particular spectral line yields the radiative lifetime of the upper state of the transition involved. For a decay where the upper state is populated only directly by the foil and not from any cascading from other excited states, the intensity may be described by

$$\ln I_\lambda = (\ln I_\lambda)_{t_0} - x/v\tau_i , \quad (4)$$

where x is the distance from the foil and v is the velocity of the beam particles.

II. EXPERIMENTAL PROCEDURE

The oxygen ion beam was provided by the Van de Graaff accelerator facility at the Air Force Cambridge Research Laboratories. The vertical orientation of this machine necessitated bending the beam 90° by an analyzing magnet. This magnetic analysis also assured the chemical purity of the beam since many gases were present in the sample bottle feeding the ion source. Excitation

of ions which occurs in the rf source decays before the ions reach the foil, since the time of flight through the accelerator is 2 to 3 orders of magnitude greater than the lifetimes measured.

Figure 1 is a representation of the apparatus used to observe the intensity of the light as a function of distance from the foil. A McPherson 1-m Czerny-Turner monochromator, with slit perpendicular to the axis of the beam, observes the beam at a fixed point in space as the foil is moved continuously. For wavelength identification the foil is held in position and the beam is scanned by the monochromator. The detector, a 6256S multiplier phototube, was cooled to $-15°C$. The output was displayed on a stripchart recorder whose motion was synchronized with either the foil or grating motion. A Fe-Ne hollow cathode lamp was used for wavelength calibration. The optical limitations of this system permitted only the most intense multiplets and members of multiplets between 2000 and 5000 Å to be observed. The recorder data for lifetimes form an exponentially decaying curve and were computer analyzed by fitting to both a single and double exponential decay with additive constant and noise. Only those data obtained while the beam current was constant were used. Table I is a listing of the experimental conditions.

TABLE I. Radiative lifetime measurements of excited ionic states in oxygen-experimental conditions.

Beam particle	$(O^{16})^+$
Beam energy	2.06 MeV
Beam current	4 μA
Foil material	Carbon
Foil thickness	20 $\mu g/cm^2$
Foil diameter (beam)	1 cm
Energy loss through foil	165 keV
Particle velocity after foil	4.8×10^{10}cm/sec
Foil travel speed	6.35 mm/min
Paper travel speed (recorder)	6 in./min
Time representation on paper	0.22 nsec/in.
Monochrometer output	6256S PM
Signal integration time	2.2 sec

III. DATA ANALYSIS

Wavelength

The measured wavelength of the observed beam lines (determined by linear interpolation between beam and calibration lines) must be corrected for the transverse (second-order) relativistic Doppler shift by use of the formula

$$\lambda_0 = \lambda(1 - \tfrac{1}{2}\beta^2), \qquad (5)$$

where λ is the observed and λ_0 the zero velocity wavelength, and β is the ratio of particle speed to light speed. This correction is about 0.4 Å at 3000 Å for 2 MeV O^+. Relativistic Doppler broadening due to the acceptance angle of the monochromator is also present and enables us to distinguish beam lines from calibration lines. The broadening is given by $\Delta\lambda = \beta\lambda_0\delta$, where δ is the acceptance angle of the monochromator and amounts to 5 Å at 3000 Å.

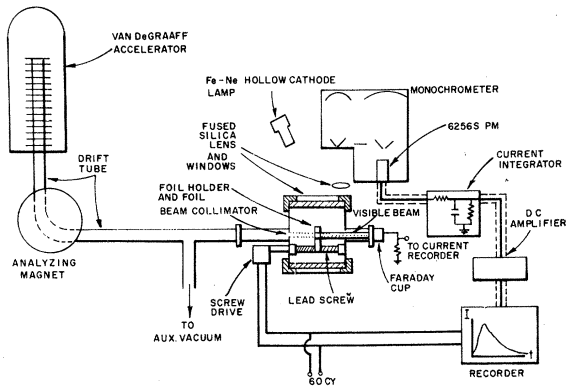

FIG. 1. Schematic diagram of experimental arrangement.

To facilitate wavelength identification and cascade analysis and to identify spectral lines not yet tabulated in the literature, a computer program (WALTRAN) was devised which predicted (from all published energy levels) all the allowed one- and two-electron transitions in oxygen. A number of previously unobserved spectral lines in oxygen were identified in this manner, and more recently published data by Bromander[5] confirmed the identifications. These are in O IV. Below are summarized the salient points of the method of spectral identification described elsewhere[4] in more detail.

(1) Since only the most intense multiplets and members of multiplets are observed (because of the slowness of the optical system), the wavelength identification and cascading analysis are greatly simplified.

(2) An attempt has been made to identify the upper and lower transitions as completely as possible even as to the total angular momentum J. Even if the J values cannot be resolved, there is no loss of information since all levels of the same configuration and designation, where splitting for different J values is small, have essentially the same lifetime.

(3) A secondary or satellite member of a multiplet cannot be present without the prime member from the same energy level.

(4) Intersystem combinations were not considered.

(5) Possible blends of lines from different multiplets and charge states were observed and are not reported here.

Cascading

A variation of the WALTRAN program, CASCAN, was used to facilitate analysis of cascades from higher-energy levels into the levels of interest. Cascading effects in the oxygen data presented here in many cases are either not allowed or negligible. Where cascading effects are neglected,

it is for one or both of the following reasons: (1) if the cascading transition is not observed but lies in the observable range (2000–7000 Å), and (2) if the cascading transition lies in the infrared, and visible or ultraviolet transitions from the same energy level are allowed. The presence of only a single exponential in the light decay curve was not used as conclusive evidence of the absence of cascading but only as an indication of the possibility of this absence. In a few cases, cascading is obvious, and in other cases, no conclusions can be made at all.

Lifetimes

The raw data, consisting of continuous curves from the recorder sheets, were fitted to both single and double exponentials with additive constant by a computerized iterative procedure. Some mathematical smoothing was used to reduce the noise. In all but a few cases, either the single exponential had the smaller standard deviation, the double reduced to a single, or the value of the second exponential became vanishingly small. The table of results (Table II) lists the following quantities in order:

(1) Measured wavelength; corrected for second-order Doppler shift and averaged over the number of measurements made on that particular line.

(2) Tabulated wavelength; values taken from the RMT,[6] UMT,[7] or NBS 4-1.[8]

(3) Lower state; term designation.

(4) Upper state; term designation.

(5) J-J; total angular momentum transition J_{lower}–J_{upper}.

(6) τ; measured lifetime of upper state in nanoseconds.

(7) Maximum difference; the maximum difference between separate measurements of the same lifetime.

(8) Average standard error; the error in τ due to the standard deviation of the raw data. This error has been averaged over the number of measurements made on the particular transition.

Transition Probabilities

Where possible, transition probabilities have been extracted from the lifetime data and are listed in Table III. When only one transition from an energy level is allowed or all but one transition from a level are negligible, then the transition probability is just the inverse of the lifetime.

IV. RESULTS

In the results presented below, a discussion of cascading possibilities is included as well as a partial listing of the transitions to lower states which contribute to the lifetime. The transitions are grouped as to charge state of the ion and are considered in order of the numerical value of the wavelength. Any comparisons with theoretical values of τ or A_{ij} are made with reference to NBS 4-1.[8]

Tabulated Transitions, O II

Five transitions were observed in O II. The upper level of two of these transitions, $4f'\,^2D^0$ and $5f\,^4F^0$, have no transitions allowed to them from higher levels, and obviously cascading is not a factor here. The remaining levels $3d'\,^2F$, $5d\,^2F$, and $5d\,^2D$ can be populated from higher levels, but from experimental observations and theoretical considerations these cascades have been neglected. The $3d'\,^2F$ level may be populated by the $4f'(^2D^0, {}^2F^0, {}^2G^0)$ levels at transition wavelengths between 4023.76 and 4060.53 Å, but these were not observed even though the $4f'\,^2D^0$ levels are known to be populated. This implies the $3d'\,^2F$–$4f'\,^2D^0$ transitions are considerably weaker than the $3d'\,^2D$–$4f'\,^2D^0$ transition observed. The red and infrared transitions to the $3d'\,^2F$ level lie between 6765 Å and 22.3 μ and are theoretically weak. The $5d\,^2F$ and ^2D levels have allowed transitions into them at wavelengths above 9500 Å originating in levels which also have considerable uv branching. The foregoing observations preclude the possibility of cascade effects on the lifetimes measured in O II.

Tabulated Transitions, O III

Of the transitions observed in O III, eight lines belonging to five different multiplets are free of cascading effects by virtue of the following reasons:

(1) Any visible transitions possible were not observed.

(2) The uv transitions possible are considerably weak, so weak that they cannot be found in any of the major tabulations.[6–9] We mention them only because they are predicted by the computer program WALTRAN.

(3) Mathematical analysis was clearly single exponential.

The pertinent upper levels are $3p\,^5S^0$, $3p\,^1D$, $3p\,^3P$, $3d\,^3F^0$, and $3d\,^5F$. The lifetimes for these levels may be compared with the theoretical calculations of Wiese[8] (Table III) and in general are in good agreement. For four other levels, the situation is not so simple and cascading may be an important factor in determining the lifetimes which we have measured. The first of these, $3d\,^3F$, has allowed single electron transitions into it from the $4p\,^3D^0$ levels at a wavelength of 2424.41 Å. This transition was faintly observed but with insufficient intensity to make meaningful lifetime measurements. By summing the transition probabilities listed in Wiese, an approximate value of τ may be obtained for the $3d\,^3F$ level. This value does not include contributions from the vacuum uv transition $2p^3\,^3D^0$–$3d\,^3F$ at 335.3 Å which may be appreciable. This theoretical value of τ is about 6.3×10^{-9} sec and, if the 335.3 Å transitions were included, would probably be considerably less. Our measured value of 10 to 11×10^{-9} sec, using the $3p\,^3D^0$–$3d\,^3F$ transitions at 3728.42 and 3728.83 Å, would then indicate mild to strong cascading may be present. We cannot say with certainty that it is not present. A nearly identical situation occurs in our measurements of the $3d\,^5D$ level. Here there are faintly observed lines which may

TABLE II. Radiative lifetimes in oxygen using the foil excitation technique

	Measured[a] wavelength (Å)	Tabulated wavelength (Å)	Lower state	Upper state	$J-J$	τ Average (10^{-9} sec)	Maximum difference (± %)	Average standard error (± %)
O II	2530.79	2530.36[b]	$3p\,^2D^0$	$3d'\,^2F$	$\frac{5}{2}-\frac{7}{2}$	0.64	3	• • •
	2805.86	2805.69[d]	$3p'\,^2D^0$	$5d\,^2F$	$\frac{5}{2}-\frac{7}{2}$	2.08	15	• • •
	2998.4	2999.49[d]	$3p\,^2P^0$	$5d\,^2D$	$\frac{3}{2}-\frac{5}{2}$	0.48	9	8
	3009.6	3009.81[d]	$3d\,^4D$	$5f\,^4F^0$	$\frac{3}{2}-\frac{5}{2}$[e]	0.64	5	8
	4343.2	4343.22[c]	$3d'\,^2D$	$4f'\,^2D^0$	$\frac{5}{2}-\frac{5}{2}$	1.16	14	• • •
O III	2686.84	2686.21[b]	$3s\,^5P$	$3p\,^5S^0$	3-2	4.20	1	11
	2983.89	2983.78[b]	$3s\,^1P^0$	$3p\,^1D$	1-2	3.25	5	3
	3024.4	3024.56[c]	$3s\,^3P^0$	$3p\,^3P$	0-1	2.20	3	4
	3046.46	3047.13[c]	$3s\,^3P^0$	$3p\,^3P$	2-2	3.36	18	2
	3260.42	3261.00[c]	$3p\,^3D$	$3d\,^3F^0$	2-3	4.81	5	1
	3264.92	3265.46[c]	$3p\,^3D$	$3d\,^3F^0$	3-4	5.13	0	3
	3350.34	3351.00[c]	$3s\,^5P$	$3p\,^5P^0$	3-3	22.8[h]	25	3
	3382.94	3382.7[c]	$3p\,^5P^0$	$3d\,^5D$	2-3[e]	25.2[h]	6	• • •
	3449.94	3450.95[c]	$3p\,^5D^0$	$3d\,^5F$	3-4	9.00	2	• • •
	3454.9	3455.15[c]	$3p\,^5D^0$	$3d\,^5F$	4-5	7.61	4	• • •
	3727.4	3728.42[c]	$3p\,^3D^0$	$3d\,^3F$	2-3	11.3[h]	22	• • •
	3729.1	3728.83[c]	$3p\,^3D^0$	$3d\,^3F$	3-4	10.3[h]	6	• • •
	3774.92	3774.00[c]	$3s\,^3P^0$	$3p\,^3D$	1-1[e]	4.67[h]	8	• • •
O IV	2384.74	2384.6[d]	$4d\,^2D$	$5f\,^2F^0$	$\frac{5}{2}-\frac{7}{2}$	0.91	8	8
	2449.76	2449.37[f]	$4f\,^2F$	$5g\,^2G^0$	$\frac{5}{2}-$	1.50	6	5
	2493.78	2493.78[d]	$3s\,^4P^0$	$3p\,^4P$	$\frac{3}{2}-\frac{5}{2}$	3.02	8	3
	2508.79	2509.23[d]	$3s\,^4P^0$	$3p\,^4P$	$\frac{5}{2}-\frac{5}{2}$	5.44	16	• • •
	2518.3	2517.39[d]	$3s\,^4P^0$	$3p\,^4P$	$\frac{5}{2}-\frac{3}{2}$	4.73	3	• • •
	2816.87	2816.53[d]	$3s\,^4P^0$	$3p\,^4S$	$\frac{3}{2}-\frac{3}{2}$	5.61[h]	2	3
	2835.88	2836.26[d]	$3s\,^4P^0$	$3p\,^4S$	$\frac{5}{2}-\frac{3}{2}$	6.03[h]	14	2
	3063.4	3063.46[c]	$3s\,^2S$	$3p\,^2P^0$	$\frac{1}{2}-\frac{3}{2}$	1.63	5	2
	3071.89	3071.66[c]	$3s\,^2S$	$3p\,^2P^0$	$\frac{1}{2}-\frac{1}{2}$	1.53	0	2
	3362.44	3362.63[c]	$3p\,^4S$	$3d\,^4P^0$	$\frac{3}{2}-\frac{3}{2}$[d]	0.96	• • •	1
	3395.94	3396.85[c]	$3s\,^4P^0$	$3p\,^4D$	$\frac{3}{2}-\frac{3}{2}$[d]	5.11	5	• • •
	3490.44	3489.89[c]	$3s'\,^2P^0$	$3p'\,^2D$	$\frac{3}{2}-\frac{5}{2}$	0.45	5	• • •
	3736.9	3736.78[c]	$3p\,^4D$	$3d\,^4F^0$	$\frac{7}{2}-\frac{9}{2}$	16.3	8	• • •
O V	2756.86	2755.12[d]	$3s\,^3P^0$	$3p\,^3P$	2-2	0.91	11	13
	2780.99	2781.04[d]	$3s\,^3S$	$3p\,^3P^0$	1-2	5.4	3	1
	2787.24	2787.03[d]	$3s\,^3S$	$3p\,^3P^0$	1-1	4.80	10	1
	4631.45	4631.12[d]	$6f\,^1F^0$	$7d\,^1D$	3-2	3.59	9	1
	4930.1	4930.27[g]	$6h\,H$	$7i\,I$		0.97	• • •	3
O VI	3432.93	3432.61[c]	$6f\,^2F^0$	$7g\,^2G$	$\frac{7}{2}-\frac{9}{2}$	0.96	10	12
	Unidentified							
	2885.83					3.86	• • •	1
	2940.87					1.85	11	4
	3464.4					1.88	5	• • •
	4644.42					2.03	9	2
	4657.42					1.60	• • •	• • •

[a] Corrected for second-order Doppler shift.
[b] UMT.
[c] RMT.
[d] WALTRAN.
[e] Principal multiplet line obscured in a blend.
[f] Bromander (Ref. 5).
[g] Bockasten *et al.* (Ref. 10).
[h] Cascading may be present.

cascade into the $3d\,^5D$ level from the $4p\,^5D^0$ and $4p\,^5P^0$ levels at between 2421 and 2489 Å. The theoretical lifetime may be obtained from Wiese[8] and is 4.85×10^{-9} sec for the $3d\,^5D$ levels. The lifetime measurement was made on the 3382.7 Å line, which is a secondary line of the multiplet $3p\,^5P^0-3d\,^5D$ (the principle line 3384.95 Å was obscured in a blend) and is about 25×10^{-9} sec. This complete disagreement and the other observations indicate extremely strong cascading effects.

Two cases of obvious cascading occurred in which both the cascading transition and the lower transition were observed and measured. The pertinent levels are the $3p\,^3D$ level, which can be populated by the $3d\,^3F^0$ level, and the $3p\,^5P^0$ level, which can be populated by the $3d\,^5D$ level. Both the $3d\,^3F^0$

TABLE III. Transition probabilities and lifetimes of some excited ionic states of oxygen.

	Wavelength (Å)	Lower State	Upper State	$J-J$	τ (Expt) Upper State (10^{-9} sec)	τ (Theor)[a] Upper State (10^{-9} sec)	A (Expt) (10^8 sec^{-1})	A (Theor)[b] (10^8 sec^{-1})
O III	2983.78	$3s\,^1P^0$	$3p\,^1D$	1 – 2	3.25	4.46	3.07	2.24
	3024.56	$3s\,^3P^0$	$3p\,^3P$	0 – 1	2.20	4.90		
	3047.13	$3s\,^3P^0$	$3p\,^3P$	2 – 2	3.36	4.90		
	3261.00	$3p\,^3D$	$3d\,^3F^0$	2 – 3	4.81	4.83		
	3265.46	$3p\,^3D$	$3d\,^3F^0$	3 – 4	5.13	4.83	1.95	2.07
	3450.95	$3p\,^5D^0$	$3d\,^5F$	3 – 4	9.00	5.98		
	3455.15	$3p\,^5D^0$	$3d\,^5F$	4 – 5	7.61	5.98	1.31	1.67
O IV	2384.6	$4d\,^2D$	$5f\,^2F^0$	$\frac{5}{2}-\frac{7}{2}$	0.91		11	
	3063.46	$3s\,^2S$	$3p\,^2P^0$	$\frac{1}{2}-\frac{3}{2}$	1.63	6.75[c]		
	3071.66	$3s\,^2S$	$3p\,^2P^0$	$\frac{1}{2}-\frac{1}{2}$	1.53	6.75[c]		
	3396.85	$3s\,^4P^0$	$3p\,^4D$	$\frac{3}{2}-\frac{3}{2}$	5.11	9.43		
	3736.78	$3p\,^4D$	$3d\,^4F^0$	$\frac{7}{2}-\frac{9}{2}$	16.3	12.5	0.61	0.80
O V	2781.04	$3s\,^3S$	$3p\,^3P^0$	1 – 2	5.40		1.85	
	2787.03	$3s\,^3S$	$3p\,^3P^0$	1 – 1	4.80		2.08	

[a]Summed from values in NBS 4-1 (Ref. 8). [b]Value in NBS 4-1 (Ref. 8). [c]Does not contain all possible transitions.

and $3d\,^5D$ levels have already been discussed. The lifetime of the $3p\,^5P^0$ levels can be extracted from Wiese and is about 6.7×10^{-9} sec whereas our measurement is 22.8×10^{-9} sec and does not represent the real lifetime of the $3p\,^5P^0$ levels. It is really a measurement of how the $3p\,^5P^0$ level is being populated by the $3d\,^5D$ level which, in turn, has cascade problems of its own from other levels.

The $3p\,^3D$ levels may be populated by a host of other levels but in this experiment all may be ruled out except for the $3d\,^3F^0$ levels which are observed. The transition measured was 3774.00 Å corresponding to $3s\,^3P^0-3p\,^3D$, J-J of 1-1, which is a weak line of the multiplet (the principle line was obscured in a blend). The upper level can be populated by the $J=2$ level of $3d\,^3F^0$ which is a strong line of the multiplet $3p\,^3D-3d\,^3F^0$. It can be shown that for such a situation the quantity measured in the decay of the lower level is more indicative of the transition probability of the cascading level than of the lifetime of the level subject to measurement. A value of the transition probability obtained from Wiese for the transition $3p\,^3D-3d\,^3F^0$, J-J of 1-2 is 1.73×10^8 sec^{-1}. When inverted, this is 5.8×10^{-9} sec and may be compared with the measured decay constant of the transition $3s\,^3P^0$-$3p\,^3D$, J-J of 1-1 of 4.67×10^{-9} sec. Wiese[8] gives a value of about 10×10^{-9} sec for τ of the $3p\,^3D$ levels.

Tabulated Transitions, O IV

Of eight different multiplets observed in O IV, seven appear to be free of cascading. One of the seven appears to have cascading because an allowed transition into it is observed but with such long lifetime (and hence small transition probability) that we have neglected it. Six lines were not listed in available tables but were predicted by WALTRAN. Subsequently these lines were classified by Bromander.[5]

The $4d\,^2D-5f\,^2F^0$ ($\frac{5}{2}$-$\frac{7}{2}$, $\frac{5}{2}$) transition at 2384.6 Å, as well as the $3s\,^4P^0-3p$ ($\frac{3}{2}$, $\frac{5}{2}$-$\frac{5}{2}$, $\frac{3}{2}$) transitions at 2493.78, 2509.23, and 2517.39 Å, can be populated from above by transitions in the visible and ultraviolet. The visible ones were not observed. The data for the latter transitions ($3s\,^4P^0-3p\,^4P$) contain considerable scatter. The transitions $3s\,^2S-3p\,^2P^0$ ($\frac{1}{2}-\frac{3}{2}$, $\frac{1}{2}$) at 3063.46 and 3071.66 Å, the transitions $3p\,^4S-3d\,^4P^0$ ($\frac{3}{2}$-$\frac{3}{2}$) at 3362.63 Å, and the transition $3s'\,^2P^0-3p'\,^2D$ ($\frac{1}{2}$-$\frac{5}{2}$) at 3489.89 Å can also be populated by transitions in both visible and near and far ultraviolet. The visible and near-ultraviolet transitions were not observed, however, and the vacuum uv transitions are theoretically weak, most having never been observed or listed in any tables but only predicted by WALTRAN. A few of these were observed by Bromander as very weak. The transition $3p\,^4D-3d\,^4F^0$ ($\frac{7}{2}-\frac{9}{2}$) at 3736.78 Å can have no allowed transitions cascading into the upper level, and hence cascading is not even possible.

The $3s\,^4P^0-3p\,^4D$ ($\frac{3}{2}-\frac{3}{2}$) transition at 3396.85 Å has predicted (WALTRAN) transitions into the upper state which lie in the vacuum and near uv. The vacuum uv transitions are not listed and must be presumed to be weak, and only one of the near uv transitions is observed, the $3p\,^4D-3d\,^4F^0$ ($\frac{7}{2}-\frac{9}{2}$) at 3736.78 Å already cited. The lifetime of the latter has been measured as 16.3×10^{-9} sec, and since this is the only transition allowed from the $3d\,^4F^0$ ($\frac{9}{2}$) level, the transition probability may be calculated immediately as 6.1×10^7 sec^{-1}, which is small. The disparity between the lifetimes of the cascading state and state of interest also indicates minimal, if any, cascading. This is not the case for the $3s\,^4P^0-3p\,^4S$ ($\frac{3}{2}$, $\frac{5}{2}-\frac{3}{2}$) transitions, however, since obvious cascading from the very strong $3d\,^4P^0$ level is observed to the $3p\,^4S$ level at 3362.63 Å already discussed. Un-

fortunately there is no way of checking the lifetime of the $3p\,^4S$ level against theoretical calculations to verify the cascading. But since the $3p\,^4S$ lifetime measured is considerably larger than the $3d\,^4P^0$ lifetime the former may be considered to be approximately correct.

Where comparisons can be made to theoretical values in NBS 4-1, our values for τ compare favorably and in some cases are even smaller than the calculated values.

Tabulated Transitions, O V

Four transitions belonging to three different multiplets were observed for O V. The upper levels involved were $3p\,^3P$, $3p\,^3P^0$, and $7d\,^1D$. The $3p\,^3P$ and $3p\,^3P^0$ levels have allowed transitions into them, predicted by WALTRAN, which lie primarily in the vacuum uv. None of these transitions are listed in the standard references but some may be found in a recent paper by Bockasten and Johansson.[10] No vacuum uv transitions into the $3p\,^3P$ levels are listed or have been observed at all, and visible transitions are not listed and were not observed in this experiment.

Some vacuum uv transitions into the $3p\,^3P^0$ levels are listed by Bockasten but their intensities are an order of magnitude less than the intensity of the measured transitions. This indicates that the contribution to the population of the $3p\,^3P^0$ levels by cascading is negligible. As for the $7d\,^1D$ level, only one transition from above is allowed and this is in the deep red and is probably negligible. The observed transition 4631.12 Å does not appear in Bockasten but we have assigned it to the combination $6f\,^1F^0$–$7d\,^1D$ (3-2).

Tabulated Transitions, O VI

Only one transition was observed which was assigned to O VI. It is $6f\,^2F^0$–$7g\,^2G$ at 3432.61 Å. Only three visible transitions are allowed into the upper state and they are not observed.

Unidentified Lines

Seven lines which could not be assigned using standard references or WALTRAN were observed. Since then two of these have been found in Bromander[5] and Bockasten.[10] These two lines are O IV, $4f\,^2F$–$5g\,^2G$ $(\frac{5}{2}-)$ at 2449.37 Å and O V, $6h\,H$–$7i\,I$ at 4930.27 Å. Cascade analyses were not made on the upper levels nor have we attempted to find all the allowed transitions from the upper level.

V. CONCLUSION

In addition to the comparison in Table III of our measured lifetimes and transition probabilities with those values available in NBS 4-1 we have also listed transition probabilites for which no theoretical comparisons are available. A few transition probabilities are given for unobserved transitions. These have been deduced by assigning the same lifetime to those terms with the same configuration and designation, where splitting for different total angular momentum values is small. Transition probabilites are extracted only where the transition is unique or dominant and when cascading is absent or negligible.

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