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LIFETIME MEASUREMENTS AND ABSOLUTE OSCILLATOR STRENGTHS FOR SOME VACUUM-ULTRAVIOLET TRANSITIONS IN O I AND O II*

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ABSTRACT

Radiative lifetimes have been measured for some resonance transitions of O I and O II in the vacuum-ultraviolet by using the beam-foil method. These results are compared with values in the existing literature, and an assessment of accuracy is made.

I. INTRODUCTION

The resonance transitions of oxygen in the vacuum-ultraviolet are especially important in the determination of the mean density of this element lying in the line of sight of various stars which have been studied with rocket-mounted spectrographs in the 1100–2500 Å region (Morton and Spitzer 1966; Stone and Morton 1967; Morton, Jenkins, and Brooks 1969). Accurate knowledge of the oscillator strengths for these transitions and those of other elements allow determinations of abundance ratios to be made, and have revealed some anomalies (Stone and Morton 1967). Also, satellite-mounted spectrographs of greater resolving power and light-gathering ability will soon be available to make similar observations in H I regions down to the Lyman limit of 912 Å (13.595 eV).

There have been four recent papers (Savage and Lawrence 1966; Gaillard and Hesser 1968; Lawrence 1969, 1970) on the determination of the absorption f-value of the O I multiplet at 1302–1306 Å, at present the crucial multiplet in determination of oxygen abundances as discussed by Stone and Morton (1967). A large amount of radiative cascading into the $2p^3(^4S)3s^3S$ upper level of the 1302–1306 Å transition was found by Gaillard and Hesser (1968) and by Lawrence (1969, 1970). Lawrence (1970) showed that the amount of cascading depended upon the parent molecule used in the dissociative-excitation process of both the modulated electron-beam method of Gaillard and Hesser (1968) and the pulsed electron-beam technique. Even in the best case observed, the ratio of the excitation cross-section of the cascading state to that of the measured state (β) was found to be $\sim$0.65, and usually it was much larger. At secular equilibrium this would imply a corresponding radiated intensity ratio of 0.42. The analysis of such decay curves can be subject to serious error as noted by Gaillard and Hesser (1968), by Lawrence (1969, 1970), and, in a more general sense, by Wiese (1970). Thus, because of the similarity of the methods which use electron excitation, the reliability of the f-value for the O I 1302–1306 Å transition may still be brought into question since neither method can avoid the large cascade correction. In view of this cascading problem, beam-foil excitation offers an alternative, and completely different, excitation method in which the cascading response evidences itself somewhat differently from the

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conventional pulse techniques. In addition, the resonance multiplet for O I at 989 Å should be investigated because of its probable importance to satellite-based observations, although Lawrence (1970) includes an experimental value for this multiplet. Similarly, other O I and O II transitions in the accessible wavelength range (700–1400 Å) should be scrutinized.

II. EXPERIMENTAL

In order to accomplish the indicated experiments, we have chosen to apply a variation of the usual beam-foil experiments. By working at low beam energies using O^+ and O^{++} beams through a magnetic isotope separator, we have emphasized the spectra of the low charge states of oxygen, i.e., O I and O II, which are dominant at beam energies below 100 keV. Spectra of higher charge states are not observed in the present experiments, although they are found in other similar experiments at higher beam energies (Martinson *et al.* 1971). Accordingly, we measured the decay down beam of vacuum-ultraviolet transitions in O I and O II atoms after foil excitation at a beam energy of 83 keV. The radiation was detected by a Bendix channeltron detector after dispersion through a 1-m normal-incidence vacuum monochromator. Carbon foils with thicknesses of 10 $\mu g\ cm^{-2}$ were used for excitation. We measured the beam velocity after the foil with an electrostatic-deflection analyzer and found it to be 0.88 mm $nsec^{-1}$ to within 4 percent (due mainly to variation in foil thickness), a value which allowed lifetimes down to ~0.2 nsec to be measured. The O I transitions at 1302–1306, 1278, 1152, and 989 Å, as well as O II transitions at 834 and 718 Å, were strongly excited, and measurements were made for these transitions (see Table 1).

The O I resonance transitions at 1039 and 1026 Å appeared weakly in our spectra. In order to obtain enough intensity to measure their radiative lifetimes we had to reduce the energy below 50 keV. At such energies it was impossible to measure the velocity after the foil, as too large a fraction of the ions were neutralized in the foil and thus prohibited electrostatic analysis. Using a calculated value for energy loss in the foil, we could determine a τ for O I 1026 Å of 3.3 nsec—a figure which we found to be reliable only to ± 50 percent, from comparisons with transitions having known lifetimes which were simultaneously measured.

Measurements of the decay curve were made with photons counted at each point for an equal amount of charge collected in a Faraday cup. The measurements were repeated several times and summed for each transition. Each decay was followed downstream from the foil until the intensity leveled out at a constant background level. The curves were then fitted by a weighted least-squares technique to a sum of two exponentials and an adjustable constant representing the background (which is a sum of the effects from dark counts, any residual gas excitation, and, if present, very long-lived cascades). The error limits are combinations of the statistical rms errors in the fitting procedure and the error in the velocity measurement.

III. RESULTS

For the 1302–1306 Å multiplet of O I, we find a $\tau = 1.79 \pm 0.17$ nsec after removal of the effect of cascading. Cascading effects were observed, but the ratio of initial radiated intensity from the cascade transition to that from the measured transition was well below those obtained (by using secular-equilibrium values corresponding to the excitation rates) in the dissociative-excitation studies previously cited. A similar result was found at higher beam energies (500 keV) by Martinson *et al.* (1971). Table 2 shows a comparison of the results mentioned here. The beam-foil method is less sensitive to the cascading effect because the δ-function–like excitation makes it possible to study the free decay from a time immediately after the excitation, when the contribution from the main decay is maximized—provided the cascade lifetime is significantly longer than the main lifetime. The cascade found for O I λλ1302–1306 (Table 2) is 30 percent shorter than the values from the previous experiments by Gaillard and Hesser (1968),

TABLE 1

LIFETIMES OF LEVELS IN O I AND O II

Spectrum	Wavelength (Å)	Combination	Mean lifetime, upper level (nsec)	Cascade lifetime (nsec)	Intensity ratio I_2/I_1 [h]	Other values (nsec)	f-value
OI	1302 - 1306	$2p^4\ ^3P\text{-}2p^3(^4S)3s\ ^3S$	1.79 ± 0.17	19 ± 5	0.13	1.82 ± 0.05[a] 1.75 ± 0.15[b] 1.70 ± 0.3[c] 2.63[d] 1.73 ± 0.52[g]	0.048 ± 0.003[f]
OI	1218	$2p^4\ ^1S\text{-}2p^3(^2P)3s\ ^1P$	0.90 ± 0.10	4.6 ± 1.1	0.09	0.9 ± 0.2[a] 1.69[d] 5.6 ± 1.7[g]	autoionizing
OI	1152	$2p^4\ ^1D\text{-}2p^3(^2D)3s\ ^1D$	1.77 ± 0.14	10 ± 2	0.08	1.9 ± 0.2[a] 1.9 ± 0.2[b] 1.9 ± 0.3[c] 2.25[d] 1.8 ± 0.6[g]	0.112 ± 0.008
OI	989	$2p^4\ ^3P\text{-}2p^3(^2D)3s\ ^3D$	3.94 ± 0.22	cascade free		4.5 ± 0.2[a] 4.35[d]	0.058 ± 0.004[f]
OI	878	$2p^4\ ^3P\text{-}2p^3(^2P)3s\ ^3P$	0.92 ± 0.09	5 ± 1	0.07	0.9 ± 0.2[a] 3.12[d]	autoionizing
OII	834	$2s^22p^3\ ^4S\text{-}2s2p^4\ ^4P$	1.26 ± 0.10	5 ± 2	0.02	1.2 ± 0.2[a] 0.71[d] 1.45[e]	0.25 ± 0.03
OII	718	$2s^22p^3\ ^2D\text{-}2s2p^4\ ^2D$	0.44 ± 0.08	2.4 ± 0.9	0.07	0.4 ± 0.1[a] 0.45 ± 0.04[b] 0.29[d] 0.51[e]	0.18 ± 0.02

a) Lawrence (1970).
b) Martinson, Berry, Bickel, and Oona (1970).
c) Gaillard and Hesser (1968).
d) Wiese, Smith, and Glennon (1966).
e) Westhaus and Sinanoglu (1969).
f) Recommended f-value from consideration of all the data discussed here.
g) Ott (1970).
h) Initial intensity ratio $I_2/I_1 = (1 - \tau_1/\tau_2)/(1 + C_1/C_2)$, where C_1/C_2 is the ratio of the exponential decay intercepts at time zero.

TABLE 2

COMPARISON OF RADIATIVE-LIFETIME DATA ON O I 1302–1306 Å

Experimenters	Mean Lifetime (τ_1) (nsec)	Cascading Lifetime (τ_2) (nsec)	Intensity Ratio I_2/I_1*
Gaillard and Hesser (1968)...	1.70±0.30	30	0.42
Lawrence (1969, 1970).....	1.82±0.05	35± 1.0	0.39
Martinson *et al.* (1971).....	1.75±0.15	33±15	0.15
Present work.....	1.79±0.17	19± 5	0.13
Ott (1970).....	1.73±0.52	...	...

* For electron excitation, we quote the intensity ratio $I_2/I_1 = 1/(1 + \sigma_{3s}/\sigma_{3p})$ at secular equilibrium. In beam-foil excitation we quote the initial intensity ratio $I_2/I_1 = (1 - \tau_1/\tau_2)/(1 + C_1/C_2)$, where C_1/C_2 is the ratio of the exponential-decay intercepts at time zero.

Lawrence (1970), and Martinson *et al.* (1971) which are close to that listed for the $3p^3P$ term (36 nsec) by Wiese, Smith, and Glennon (1966). This demonstrates that the cascading in the above studies most probably comes primarily through the O I $3s^3S$–$3p^3P$ multiplet at 8447 Å. It is important to note that the main lifetime (1.79 nsec) was rather insensitive to variations of the cascading lifetime and the background. This is partly due to the fact that the decay of the upper level has very little effect on the main decay initially, since the experiment starts very near $t = 0$ for the first downstream points. Thus we can conclude that, within the published error limits, our results and those of Gaillard and Hesser (1968), Lawrence (1969, 1970), and Martinson *et al.* (1971) are in complete agreement. The absolute oscillator strength (f-value) for O I λλ1302–1306 may be reliably considered to equal 0.048 ± 0.003, the average of all these results.

This agreement between two rather different methods must be regarded as strong evidence that reliable cascade corrections can be made routinely on decay curves (or curves of phase shift versus frequency) when the cascading is reasonably well understood and the two lifetimes are well separated.

As pointed out by Lawrence (1970), for O I the upper states of all the transitions studied here except 1302 Å are populated by cascading from higher states which can autoionize, thereby reducing cascade effects. Lawrence (1970) found these transitions to be cascade-free to within 5 percent. Our measurements, however, indicate cascading in excess of 5 percent, except for the 989 Å multiplet for which a cascade-free decay was observed. Cascading into the other upper states studied is definitely present, and may be understood from the observation, in emission, of some of the possible cascading levels (Eriksson and Isberg 1968). The rather short-lived cascades found may well result from the competition between autoionization and the radiative process. Accordingly, no definite assignment of the levels responsible for the cascading is possible. The shortening of the radiative lifetimes of the 878 and 1218 Å upper states of O I from the predicted values of Wiese *et al.* (1966) is assumed due to the autoionization from state mixing discussed by Lawrence (1970). The radiative-transition probability of $2p^4\,{}^1S$–$2p^3(^2P)3s\,{}^1P$ of Ott (1970), and the theoretical branching ratio of the two allowed radiative decays from the $2p^3(^2P)3s\,{}^1P$ level (Wiese *et al.* 1966), allow us to give a nonradiative transition probability ($A_{\text{total}} - A_{\text{radiative}}$) of 5.8 ± 1.5 × 10^8 sec^{-1} for the autoionization affecting this level.

The mean lives, in all cases studied in common, are in excellent agreement with those of Lawrence (1970) and Martinson *et al.* (1971), with the sole exception of the mean life of the upper state of the 989 Å multiplet, which was measured only by Lawrence (1970). The statistical-error limits fail to overlap. The source of this slight discrepancy is obscure but is probably systematic since 989 Å was very intense, yielding the best-determined decay curves of our study, which showed, as noted already, a simple exponential

decay. This means that the statistically derived error limits cannot be reliable. In any case, the increasing of the maximum probable error to 7 percent allows the values to overlap, and thus we recommend that $\tau = 4.22 \pm 0.28$ nsec be used for the upper-state radiative lifetime of the O I 989 Å multiplet.

Two O II transitions were also measured, $2s^22p^3\ {}^4S$–$2s2p^4\ {}^4P$ at 834 Å (a resonance transition) and $2s^22p^3\ {}^2D$–$2s2p^4\ {}^2D$ at 718 Å. The main lifetimes found here were also in excellent agreement with Lawrence (1970) and Martinson *et al.* (1971), where states in common were studied, except that once again cascading was found by both beam-foil studies but not by Lawrence (1970). This may result from the increased severity of the excitation by a foil compared with excitation by 40–200 V electrons, resulting in increased excitation of higher-lying levels. As noted above, although autoionization depletes the cascading levels, the observed cascading amounts are not unexpected in view of the observation of these cascading levels in emission. The autoionization occurs through small configurational interactions with allowed autoionizing states, and is thus weak for these transitions. The O II transitions studied here cannot be observed in absorption in the H I regions, but may be of value in solar studies.

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