Oxygen Metastable X-Ray Emitters*

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A crystal spectrometer is used to study 6.5-MeV, foil-excited oxygen-beam x rays. The transitions from $(1s)\,(2p)\;2\,^3P$ to $(1s)^2 1\,^1S_0$ He-like and from $(1s)\,(2s)\,^4P^\circ$ to $(1s)^2(2s)\,^2S_{1/2}$ Li-like oxygen states are observed to have lifetimes of 1.47 ± 0.02 and 1.87 ± 0.1 nsec, respectively. Both decays are observed to have long-lived components. These results are compared to previous lifetime measurements of x-ray emitting and electron-emitting oxygen states.

In a recent paper[1] we have reported the measurement of lifetimes of He-like and Li-like metastable x-ray emitting states of fluorine. These measurements, made with a high-resolution curved-crystal spectrometer, confirmed the lifetime determination of the $^3P_1$ decay measured by Mowat *et al.*[2] using a Si(Li) detector, and yielded the lifetime of a ^4P decay of the three-electron fluorine system. The purpose of the present paper is to extend these measurements to oxygen. The $^3P_1$ lifetime of the two-electron oxygen system has been reported previously by Sellin *et al.*[3,4] in both a low-energy-resolution and a high-energy-resolution experiment. The high-resolution experiment, performed with a plane-crystal spectrometer, had sufficient resolution to separate the ^3P and ^4P states; however, due to low counting rates only the ^3P lifetime was determined. In the present experiment we obtain lifetime data on both the ^3P and ^4P transitions. These data are also compared to recent lifetime measurements of Moore *et al.*[5]

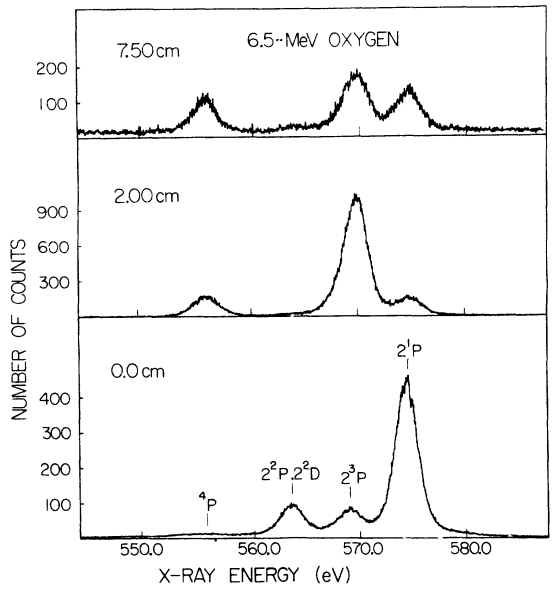

FIG. 1. Oxygen-beam x-ray spectra in the energy range of 545 – 590 eV. The $E1$ transition from the 2^1P_1 to the 1^1S_0 of He-like fluorine is indicated. This transition is prompt and is seen downstream from the target due to cascading from long-lived states at high excitation. The doublet Li-like states indicated in the figure are also seen very weakly downstream due to cascading. The metastable 2^3P and 2^4P states are easily seen 2.25 nsec (2.0 cm) and 8.46 nsec (7.5 cm) after excitation.

The present experiment was performed with the Kansas State University tandem Van de Graaff accelerator. The lifetimes were determined by measuring the x-ray intensities with a vacuum curved-crystal spectrometer as a function of time of flight of the oxygen metastable states produced in a thin C foil (20 $\mu g/cm^2$). The experimental setup is the same as discussed in Ref. 1. The lifetime measurement was performed with a 6.5-MeV oxygen beam and tracked over several lifetimes of the metastable decay. This was done in order to see if long-lived components are present. The energy calibration is based on the $^1P_1$ and $^3P_1$ energies measured by Tyrén.[6]

Figure 1 contains the foil-excited oxygen-beam x-ray spectra in the 45-eV interval between 545 and 590 eV with the C foil at 0.0 cm (prompt), 2.0 cm (2.25 nsec), and 7.5 cm (8.46 nsec) upstream

TABLE I. Calculated lifetimes of one electron $E1$ transitions from states with $l = n - 1$ for oxygen.

Initial state n_i	Initial state l_i	Final state n_f	Final state l_f	Branching ratio %	Lifetime (nsec) $Z=8$	Lifetime (nsec) $Z=9$
12	11	11	10	100	5.23	3.27
11	10	10	9	100	3.36	2.10
10	9	9	8	100	2.06	1.29
9	8	8	7	100	1.20	0.75
8	7	7	6	100	0.66	0.41
7	6	6	5	100	0.33	0.21
6	5	5	4	100	0.15	0.09
5	4	4	3	100	0.06	0.04
4	3	3	2	100	0.02	0.01
3	2	2	1	100	0.004	0.002
2	1	1	0	100	0.0004	0.0002

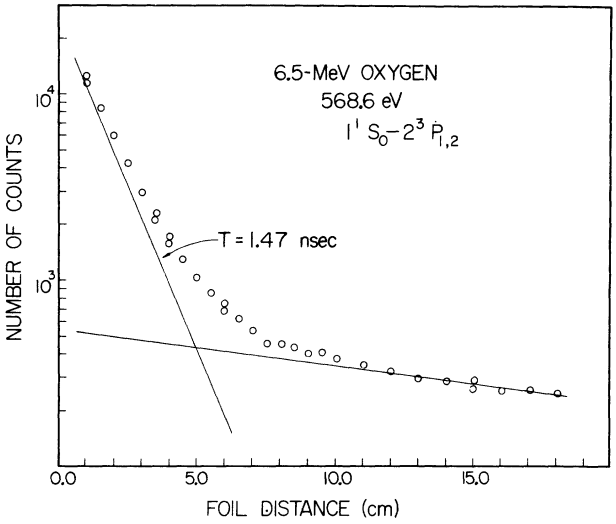

FIG. 2. Decay curve for the He-like 1^1S_0 $(1s)^2$-$2^3P(1s)(2p)$ transition. The short-lived component has a 1.47-nsec lifetime and is identified with the decay of the 2^3P_1.

from the spectrometer. The largest peak in the prompt spectrum is the $E1$ decay of the $(1s)(2p)$ $^1P_1$ to the $(1s)^2\,^1S_0$ ground state of the He-like oxygen. The next-largest peak in the prompt spectrum is due to the decay of the $(1s)(2s)(2p)$ 2^2P and 2^2D states of the Li-like oxygen and is not seen downstream with appreciable strength. The two remaining peaks are seen strongly downstream

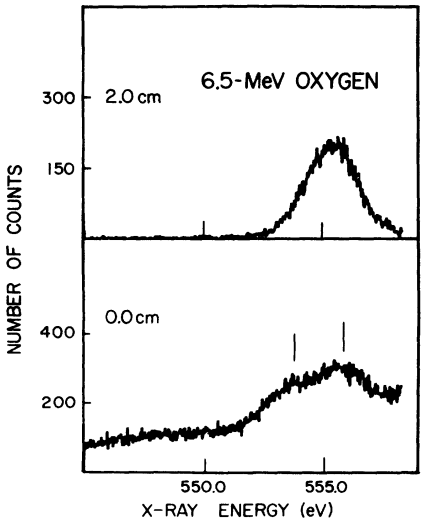

FIG. 3. Two partially resolved states at 553.7 and 556.2 eV are observed in the prompt spectrum. Only the 556.2-eV state is seen in the 2.25-nsec (2.0-cm) downstream spectrum and identified with the Li-like ^4P transition.

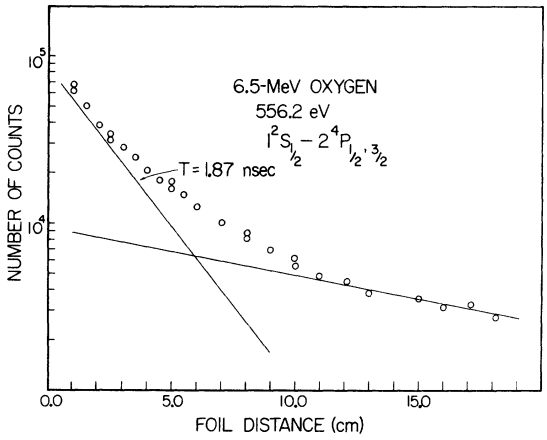

FIG. 4. Decay curve for the Li-like $1^2S_{1/2}(1s)^2$ $(2s)$-$2^4P(1s)(2s)(2p)$ transition. The short-lived component has a 1.87-nsec lifetime that is probably due to the $2^4P_{3/2}$ transition.

and correspond to the $(1s)^2\,^1S_0$-$(1s)(2p)\,^3P$ He-like and $(1s)^2(2s)\,^2S_{1/2}$-$(1s)(2s)(2p)\,^4P$ Li-like oxygen transitions.

The H-like and He-like (np)-$(1s)$ transitions of fluorine[1,7] and oxygen[5,8] are all seen weakly downstream from a foil. At first it may seem remarkable that the allowed $E1$ transitions are seen downstream from the foil at times greater than 1 nsec. A simple exercise illustrates that some intensity should be expected. Table I gives the expected lifetimes for one-electron atoms with $Z=8$ and 9 scaled from the hydrogen lifetimes.[9] It can be seen that any state formed with $l=n-1$ eventually leads to a $(2p)$-$(1s)$ transition with a 100% branching ratio. Also from the table it is seen that states with $l=n-1$ for $n\geq 9$ have lifetimes greater than 1 nsec. Since the intensities seen downstream are several orders of magnitude less than those at the foil, very little of the initial population of states need be caught up in such a cascade to explain the observation of the allowed $(2p)$-$(1s)$ transition downstream from the foil. Other high n- and l-value states $(l<n-1)$ with lifetimes greater than 1 nsec lead to $(2p)$-$(1s)$ transitions with a much smaller branching ratio and also lead to $(3p)$-$(1s)$ transitions, $(4p)$-$(1s)$ transitions, and higher-order transitions.

TABLE II. 6-MeV oxygen decay-curve results.

		τ(nsec)	
E(eV)	Transition	Fast	Slow
568.6	$1^1S_0(1s^2)-2^3P(1s)(2p)$	1.47 ± 0.02	20 ± 3
556.2	$1^2S_{1/2}(1s)^2(2s)-2^4P(1s)(2s)(2p)$	1.87 ± 0.1	8 ± 1

TABLE III. Oxygen x-ray emission and autoionization lifetime data.

			^3P		^4P	
Reference	Beam energy (MeV)	Detector	E [a] (eV)	τ(nsec)	E [b] (eV)	τ(nsec)
c	6–42	Geiger counter	569	1.7 ± 0.3	···	···
d	20	Plane-crystal spectrometer	569	1.5 ± 0.1	···	···
e	8, 16	Curved-crystal spectrometer	568.6	1.48 ± 0.08	554.2	3.48 ± 0.08
Present	6	Curved-crystal spectrometer	568.6	1.47 ± 0.02	556.2	1.87 ± 0.1
f	2.5–20	Electron spectrometer	···	···	417.3	$25 \pm 2 (J = \frac{5}{2})$ $< 2 (J = \frac{1}{2}, \frac{3}{2})$

[a] Transition energy for $1\,^1S_0$-$2\,^3P_1$ x ray.
[b] Transition energy for $1\,^2S_{1/2}$-$2\,^4P$ x ray or $1\,^1S$-$2\,^4P$ electron.
[c] Reference 3.
[d] Reference 4.
[e] Reference 5.
[f] Reference 11 and 12.

Figure 2 contains the presently observed decay curve for the 1^1S_0-$2^3P_{1,2}$ He-like transition in oxygen for 6.5-MeV beam energy. The curve spans a time interval of approximately 1–20 nsec after excitation. A fast component of 1.47 ± 0.02 nsec and a slow component of 20 ± 3 nsec were extracted by a least-squares fit. The fast component is assigned to the 2^3P_1 initial state as in the F case and agrees with previous measurements.[2,5] The slow component of the decay curve yields a lifetime greater than the theoretical lifetime[10] of 12.6 nsec for the 2^3P_2 state. The 1^1S_0-2^3P_1 decay cannot be energetically resolved from the 1^1S_0-2^3P_2 $M2$ decay. The discrepancy between the measured value of the slow component and the expected lifetime of the 2^3P_2 state may be due to cascading through the 2^3P_1 state.

Figure 3 shows the x-ray spectrum in the region from 545 to 560 eV. The prompt spectrum contains two unresolved transitions at 553.7 and 556.2 eV, whereas only the higher-energy transition is observed downstream. The decay curve of the 556.2-eV transition in the interval of 1–20 nsec is given in Fig. 4. A least-squares fit was used to obtain a fast component of 1.87 ± 0.1 nsec and a slow component of 8 ± 1 nsec. Moore *et al.*[5] report a lifetime of 3.48 ± 0.08 nsec and they do not see a slow component. The extracted lifetimes are not consistent within experimental error. This discrepancy may be due to an unobserved slow component in the data of Ref. 5, or it could be due to differences in the relative populations of the ^4P_j states with different j values as a function of incident-ion energy. The present results are for 6.5-MeV incident energy, while those of Ref. 5 are for 8 and 16 MeV. Tables II and III summarize the present and previous experimental results for oxygen.

The lifetime of the $^4P_{5/2}$ state in Li-like oxygen has been measured to be 25 ± 3 nsec by Donnally *et al.*[11] by observing the electrons from autoionization. These authors attribute a fast component of less than 2 nsec to the $j = \frac{1}{2}$ and $j = \frac{3}{2}$ components of the ^4P_j multiplet. Their measurements were made with incident energies of 2.5–20 MeV. These results for the lifetimes of the $j = \frac{1}{2}$ and $j = \frac{3}{2}$ components are consistent with the present x-ray measurements, whereas the slow component they attribute to the $j = 5/2$ state is too slow to account for the slow component seen with x rays.

Sellin[12] gives semiemperical scaling rules for the $^4P_{5/2}$, $^4P_{3/2}$, and $^4P_{1/2}$ states, which predict lifetimes for oxygen of 42, 0.5, and 0.08 nsec, respectively. These values suggest that the 1.87-nsec lifetime of oxygen observed in the present experiment is due to the $^4P_{3/2}$ state. This same scaling law predicts a 0.25-nsec lifetime for the $^4P_{3/2}$ in fluorine, compared with the previously reported value of 2.0 nsec.[1]

In summary, we report on new measurements for the lifetimes of ^3P and ^4P states of oxygen and compare them to previous x-ray and electron measurements. It is also demonstrated that excitation of high-n- ($n > 9$) high-l-value states of H-like and He-like oxygen and fluorine can lead to the observation of allowed (np)-($1s$) transitions at times greater than 1 nsec via cascading.

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[1]P. Richard, R. L. Kauffman, F. F. Hopkins, C. W. Woods, and K. A. Jamison, Phys. Rev. Lett. 30, 888 (1973).

[2]J. R. Mowat, I. A. Sellin, R. S. Peterson, D. J. Pegg, M. D. Brown, and J. R. Macdonald, Phys. Rev. A 8, 145 (1973).

[3]I. A. Sellin, B. L. Donnally and C. Y. Fan, Phys. Rev. Lett. 21, 717 (1968).

[4]I. A. Sellin, M. D. Brown, W. W. Smith and B. L. Donnally, Phys. Rev. A 2, 1189 (1970).

[5]C. F. Moore, W. J. Braithwaite, and Dennis L. Matthews (unpublished).

[6]F. Tyrén, Nova Acta Reg. Soc. Sci. Ups. 12, 1 (1940).

[7]Robert L. Kauffman, C. W. Woods, F. F. Hopkins, D. O. Elliott, K. A. Jamison, and P. Richard, J. of Phy. B (to be published).

[8]D. L. Matthews, W. J. Braithwaite, and C. Fred Moore (unpublished).

[9]W. N. Lennard (private communication).

[10]G. W. F. Drake, Astrophys. J. 158, 1199 (1969).

[11]B. Donnally, W. W. Smith, D. J. Pegg, M. Brown, and I. A. Sellin, Phys. Rev. A 4, 122 (1971).

[12]M. Levitt, R. Novick, and P. D. Feldman, Phys. Rev. A 3, 130 (1971).