Extreme ultraviolet spectra of highly ionized oxygen and fluorine*

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The foil-excitation method has been used to study the extreme ultraviolet spectra of highly ionized oxygen and fluorine. Several previously unreported lines in heliumlike fluorine are reported and other newly reported lines in heliumlike oxygen have been measured to higher accuracy. Included in the measurements are certain heliumlike oxygen transitions of significance in interpretation of solar-flare spectral observations. The wavelength determinations are usually in good agreement with calculated results which includes relativistic corrections but discrepancies arise when nonrelativistic calculations are used. A comparison of the present results and those recently obtained by θ-pinch and laser-induced plasma sources is made for both heliumlike and lithiumlike ions; a few discrepancies occur, with our results in most cases in better agreement with relativisitically corrected calculations. Certain unidentified lines in the spectra may be attributable to radiative transitions between quartet states of lithiumlike ions.

INTRODUCTION

We have used the foil-excitation method to study the extreme ultraviolet spectra of highly ionized oxygen and fluorine in the wavelength region ~70–230 Å. The spectra, examples of which are shown in Figs. 1 and 2, contain lines from one- to five-electron ions including several transitions in F VIII that have not been previously reported. In addition, we have improved considerably on the accuracy of several recently reported new lines in OVII. Included in the measurements are certain transitions in OVII that are of significance in the interpretation of solar-flare spectral observations. In particular, the line observed at 100.20 Å, which is identified with the transition $2\,^1P$-$4\,^1D$ in OVII, was observed in recent solar-flare spectra.[1]

The classic spark-source work of Edlén[2,3] is mostly limited to transitions in three-or-more-electron oxygen and fluorine in the spectral region 70–230 Å. Only recently have extensive investigations of OVII and FVIII been made possible by the use of θ-pinch[4] or laser-induced[5,6] plasma sources. This plasma work appears spectroscopically superior to the beam-foil studies on oxygen by Buchet *et al.*[7] and Bromander.[8] The main purpose of the work of Buchet *et al.*[7] was to measure radiative decay times; the wavelength determinations were limited in accuracy to ±0.5 Å in the spectral region of interest. We have improved the sensitivity and signal-to-noise ratio of the foil-excitation technique through pulse counting and digital (stepping) data acquisition with consequent improvement in the accuracy of wavelength determination. The present results are comparable in accuracy (±0.05 Å) to those obtained using the aforementioned plasma sources, and of considerably higher accuracy than the previous beam-foil observations of Buchet *et al.*[7]

Gabriel[9] pointed out that the beam-foil source appears to be similar in many respects to sources such as laser-induced plasmas which show local thermodynamic equilibrium populations of the higher excited states. Thus one observes, in both sources, intense lines from states of high n and high l. The over-all agreement in the results obtained by the beam-foil source and the plasma sources seems quite reasonable but some discrepancies are apparent as can be seen from Tables I and II, where our results for heliumlike and lithiumlike oxygen and fluorine are listed, respectively, and are compared to other experimental observations and theoretical calculations. An example of such a discrepancy concerns the $2\,^3P^0$ – $3\,^3S$ transition in OVII. The present result is 132.81 ± 0.05 Å and a θ-pinch plasma-source measurement of Peacock[4] gives the wavelength of this transition to be 133.31 ± 0.05 Å. The relativistically corrected theoretical result shown in Table I is 132.759 Å. The decays in flight of foil-excited ions occur in vacuum and are thus likely to be less prone to Stark perturbations than such sources as laser-induced plasmas.

METHOD

High-energy oxygen- and fluorine-ion beams from the Oak Ridge National Laboratory tandem accelerator were passed through thin (~20 $\mu g/cm^2$) carbon foils which served to excite the ions and strip them further. The incident-beam energies were chosen to maximize the particular charge

TABLE I. Heliumlike transitions.

Transition	O VII Measured λ (Å)	O VII Other observations	O VII Rel.	O VII Theory Nonrel.	F VIII Measured λ (Å)	F VIII Other observations	F VIII Rel.	F VIII Theory Nonrel.
$2\,^3S$-$3\,^3P^o$	120.33	120.37[a], 120.331[b], 120.3[c]	120.340[d]	120.506[d], 120.505[e]	93.22[f]	93.21[g], 93.23[h]	93.244[d]	93.408[d], 93.407[e]
$2\,^3S$-$4\,^3P^o$	91.11[f]	91.02[a], 91[c]	91.091[d]	91.199[d]	70.4 ± 0.1[f]	70.39[g], 70.41[h]	70.409[d]	70.516[d]
$2\,^1P^o$-$3\,^1S$	137.51	138[c]	137.542[d]	137.578[d]	104.94	...	104.994[d]	105.029[d]
$2\,^1P^o$-$3\,^1D$	135.79	135.5[c]	...	135.910[e], 135.912[i]	103.79	103.79[g]	...	103.914[e], 103.915[i]
$2\,^1P^o$-$4\,^1D$	100.20	100[c]	...	100.284[i]	...	76.62[g]	...	76.703[i]
$2\,^3P^o$-$3\,^3S$	132.81	133.31[a], 133.3[c]	132.759[d]	132.803[d]	101.55	...	101.674[d]	101.722[d]
$2\,^3P^o$-$3\,^3D$	128.49	128.44[a], 128.462[b,j], 128.5[c]	...	128.518[e], 128.519[h]	98.69[k]	98.753[f,b]	...	98.823[e], 98.823[i]
$2\,^3P^o$-$4\,^3D$	96.12[f]	96.12[a], 96.1[c]	...	96.184[i]	...	73.82[g], 73.83[h]	...	73.881[i]
$2\,^2P^o$-$5\,^2D$	86.1 ± 0.1[f]	86.07[a], 86.1[c]	...	...	...	66.11[f], 66.13[h]	...	...

[a] Reference 4.
[b] Reference 11.
[c] Reference 7.
[d] Reference 12, using only $J = 1$ levels of triplet P states.
[e] Reference 13.
[f] Wavelength observed in second order.
[g] Reference 6.
[h] Reference 5.
[i] Reference 14, lower-level values of Ref. 13.
[j] Wavelengths weighted according to intensities in Ref. 10.
[k] Possible blend with $2\,^1S$-$3\,^1P^o$ transition.

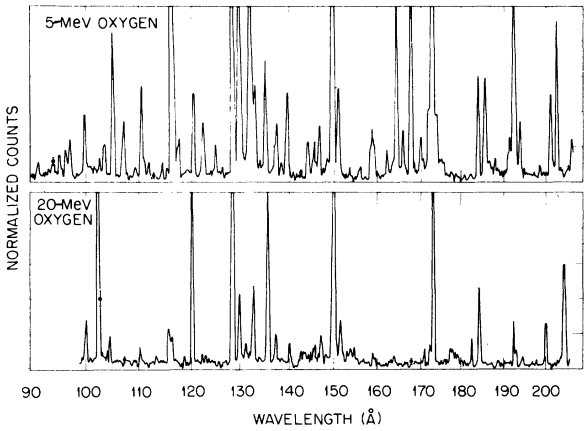

FIG. 1. Beam-foil spectra of highly ionized oxygen taken at beam energies of 5 (upper) and 20 MeV (lower).

states of interest. In this experiment 5- and 20-MeV oxygen beams and 5-, 10-, and 22.5-MeV fluorine beams were used.

Radiation emitted at 90° to the beam axis by the decay in flight of foil-excited ions was dispersed by a 2.2-m grazing incidence spectrometer. The gold-coated (300 grooves/mm) concave grating used in the instrument had a blaze angle of 2° 4′ (blaze wavelength of 191 Å at the angle of incidence of $87\frac{1}{2}°$). A channeltron detector was used at the exit slit of the spectrometer. A 90% transmission grid was used to bias out stray electrons. The spectrometer was stepped in discrete wavelength intervals and the detector output, which was normalized to constant amounts of collected charge

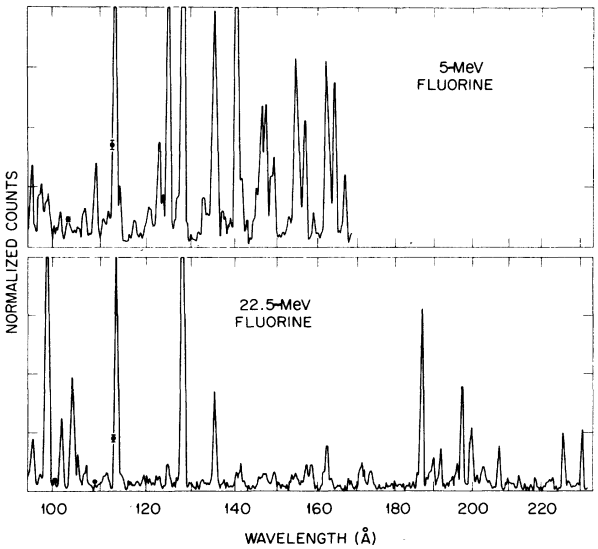

FIG. 2. Beam-foil spectra of highly ionized fluorine taken at beam energies of 5 (upper) and 22.5 MeV (lower).

TABLE II. Lithiumlike transitions.

Transition	O VI Measured λ (Å)	O VI Other observations	F VII Measured λ (Å)	F VII Other observations
$(2s)\,^2S-(3p)\,^2P^o$	150.08	150.10[a], 150.101[b,c], 150.1[d]	112.97	112.953[b,c]
$(2s)\,^2S-(4p)\,^2P^o$	115.83	115.88[a], 115.824[b,c], 115.8[d]	86.8±0.1[e]	86.728[c]
$(2s)\,^2S-(5p)\,^2P^o$	104.78[f]	104.79[a], 104.811[b]	78.4±0.1[e]	78.36[g]
$(2s)\,^2S-(6p)\,^2P^o$	99.68	99.68[a]	74.5±0.1[e]	74.47[g]
$(2s)\,^2S-(7p)\,^2P^o$	96.86	96.78[a]	•••	72.30[g]
$(2s)\,^2S-(8p)\,^2P^o$	95.07	95.02[a]	•••	71.00[g]
$(2s)\,^2S-(9p)\,^2P^o$	93.82	93.84[a]	•••	•••
$(2p)\,^2P^o\,(3s)\,^2S$	184.08	184.05[b,c], 184[d]	134.86	134.822[b,c]
$(2p)\,^2P^o-(4s)\,^2S$	132.3±0.1	132.24[a], 132.281[b,c]	•••	97.32[g]
$(2p)\,^2P^o-(5s)\,^2S$	117.30	117.40[a]	•••	86.47[g]
$(2p)\,^2P^o-(3d)\,^2D$	173.04	173.03[b,c], 173[d]	127.75	127.732[b,c]
$(2p)\,^2P^o-(4d)\,^2D$	129.85	129.82[a], 129.843[b,c], 129.8[d]	95.74	95.77[b,c]
$(2p)\,^2P^o-(5d)\,^2D$	116.40	116.43[a], 116.397[b,c]	•••	85.80[g]
$(2p)\,^2P^o-(6d)\,^2D$	110.22	110.25[a], 110.199[b,c]	•••	81.18[g]
$(2p)\,^2P^o-(7d)\,^2D$	106.81	106.79[a]	•••	78.66[g]
$(2p)\,^2P^o-(8d)\,^2D$	•••	104.67[a]	•••	77.08[g]
$(2p)\,^2P^o-(9d)\,^2D$	103.22	103.26[a]	•••	76.05[g]
$(2p)\,^2P^o-(10d)\,^2D$	102.37	102.30[a]	•••	•••

[a] Reference 4.
[b] Wavelengths weighted according to intensities tabulated by Kelly (1968).
[c] References 2 and 3.
[d] Reference 7.
[e] Wavelength observed in second order.
[f] Possible blend with $(2p)\,^2P^o-(8d)\,^2D$ line.
[g] Reference 5.

from the beam, was stored in a multichannel scaler that was synchronized with the stepping process.

RESULTS

Observations of the spectra of the more highly stripped members of the helium isoelectronic sequence are of considerable interest since in principle one can measure the relativistic corrections to precisely calculated nonrelativistic energy eigenvalues. Table I shows our results for transitions in heliumlike oxygen and fluorine along with other experimental observations and recent theoretical predications. The accuracy of our wavelength determinations is estimated to be ±0.05 Å unless otherwise stated in the tables. This uncertainty estimate is based upon both calibration measurements and the general reproducibility of the wavelengths of the foil-excited spectral lines relative to certain well-established lines within the spectra themselves.

The spectrometer was calibrated against 39 well-known lines in O I, N I, H I, He I, and He II obtained from a hollow cathode source, and the rms value of the resulting error curves was used as an uncertainty estimate. In addition, certain lines, such as those originating from hydrogenic transitions in the foil-excited source, were used as inboard reference lines. Consistency checks with other established lines of heliumlike, lithiumlike, and berylliumlike ions were found to be entirely satisfactory. Since the Doppler correction factors are the same for both measured and inboard reference lines, this inboard calibration procedure completely avoids the need for Doppler corrections to measured wavelengths.

We obtain good agreement with the results of Accad *et al.*,[12] who include relativistic corrrections (see Table I) in their calculations of the energies of S and P states in the helium sequence. Discrepancies are apparent in cases where the measurements are compared with theoretical predictions obtained using nonrelativistic calculations of the energies of S, P, and D states.

In addition to the lines cited in Table I, certain blended lines which appear in the fluorine spectra at 200.1 and 170.9 Å may be attributable to the transitions $3\,^{1,3}D$-$5\,^{1,3}F^\circ$ and $3\,^{1,3}D$-$6\,^{1,3}F^\circ$, respectively. Such wavelengths are in reasonable agreement with the calculations of Brown[15] and have apparently not been previously reported. Brown[15] obtained the values of 200.24 Å for the $3\,^1D$-$5\,^1F^\circ$ transition, 200.05 Å for the $3\,^3D-5\,^3F^\circ$

TABLE III. Unidentified transitions.

Measured λ (Å)	Tentative assignment	Calculated λ (Å)
	Oxygen	
109.1 ± 0.1	...	
111.6 ± 0.1	$(1s2s2p)\,^4P^o - (1s2s5s)\,^4S$	111.3[a], 110.1[b]
114.1 ± 0.1	$(1s2p^2)\,^4P - (1s2p4d)\,^4D^o$	114.5[b], 114.4[c]
140.10 ± 0.05	$(1s2s2p)\,^4P^o - (1s2s3d)\,^4D$	140.1[b], 137.6[c]
145.95 ± 0.05	$(1s2p^2)\,^4P - (1s2s5p)\,^4P^o$	145.9[b]
	Fluorine	
106.7 ± 0.1	$(1s2s2p)\,^4P^o - (1s2s3d)\,^4D$	106.4[b], 103.4[c]
110.5 ± 0.1	$(1s2p^2)\,^4P - (1s2s5p)\,^4P^o$	110.4[b]
111.7 ± 0.1	$(1s2p^2)\,^4P - (1s2p3d)\,^4D^o$	111.6[b], 109.4[c]
114.2 ± 0.1	...	
117.1 ± 0.1	...	

[a] Reference 18.
[b] Reference 19.
[c] Reference 20. (Use lower level of Ref. 18.)

transition, 170.87 Å for the $3\,^1D - 6\,^1F^\circ$ transition, and 170.73 Å for the $3\,^3D - 6\,^3F^\circ$ transition.

Results for transitions observed in lithiumlike oxygen and fluorine are shown in Table II along with other experimental observations. Several lines in both the spectra of oxygen and fluorine may be attributable to radiative transitions between core-excited quartet states of lithiumlike ions. These states have been previously studied[16,17] through their forbidden autoionizing decay channel. Nonrelativistic calculations have been made on the energies of such states by Holøien and Geltman,[18] Junker and Bardsley,[19] and Berry.[20] The present results are shown in Table III along with possible transition assignments and their theoretically predicted wavelengths.

Our present results for four- and five-electron ions are in good agreement with the higher resolution and more precise work of Edlén[2,3] to within our accuracy and are not duplicated here.

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