Transitions of the type 2*s*–2*p* in oxygenlike Y, Zr, and Nb

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Transitions of the type 2*s*–2*p* in the oxygenlike ions Y XXXII, Zr XXXIII, and Nb XXXIV were identified in spectra recorded at the University of Rochester's Omega laser facility. Solid targets were spherically irradiated by 24 beams of frequency-tripled (351-nm) Nd:glass laser radiation. The spectra were photographed with a 3-m grazing-incidence spectrograph. The identified transitions of the oxygenlike ions are in the range 30 to 73 Å. The wavelengths for the magnetic-dipole transitions within the $2s^22p^4$ ground configurations of these ions are predicted from the experimental energy levels.

INTRODUCTION

In recent observations of laser-produced plasmas at the Omega laser facility at the University of Rochester, 2*s*–2*p* transitions were identified in carbonlike, nitrogenlike, oxygenlike, and fluorinelike ions of Cu, Zn, Ga, and Ge (Ref. 1) and in oxygenlike and fluorinelike ions of As, Se, Br, and Rb.[2] These spectra were produced by the spherical irradiation of solid targets by six frequency-tripled (351-nm) beams of the Omega laser.[3] In this paper, we discuss the extreme ultraviolet spectra produced by irradiating solid targets by 24 frequency-tripled laser beams. We report wavelength measurements for 2*s*–2*p* transitions in the oxygenlike ions Y XXXII, Zr XXXIII, and Nb XXXIV. From the energy levels derived from these measurements, the wavelengths of the magnetic-dipole transitions within the $2s^22p^4$ ground configurations of these ions are predicted. These longer-wavelength transitions are useful for the diagnosis of tokamak plasmas.

EXPERIMENT

The targets were irregularly shaped solid pieces of Y, Zr, or Nb/Fe alloy and were approximately 400 μm in diameter. Each target was attached to a thin glass stalk by using a silicone adhesive. Each of the 24 laser beams was focused by *f*/3.7 focusing optics to a point eight target radii beyond the center of the target. With this focusing arrangement, the outer edge of each beam was nearly tangent to the target surface. Each beam delivered an energy of approximately 50 J in a pulse of 600-psec duration. The average laser intensity at the target surface was typically 4×10^{14} W/cm^2.

The spectra from 15 to 370 Å were photographed by a 3-m grazing-incidence spectrograph[4] fitted with a gold-coated Bausch & Lomb replica grating having 1200 lines/mm. The angle of incidence was 88°, and at this angle the blaze wavelength of the grating was 127 Å. Light from the target was focused astigmatically onto the spectrograph entrance slit by a cylindrical beryllium mirror that was positioned 50 cm in front of the entrance slit and 1.3 m from the target. The linear image formed by the mirror was adjusted to cross the entrance slit at an angle of 1°; this provided some spatial resolution in the recorded spectrum. The spectra were recorded on Kodak 101-05 plates. Two or three laser shots were used for each exposure.

The reference spectra consisted of lines of Si XI, Si XII, C VI, and O VI originating in the glass stalk and the adhesive. Although the differing spatial origins of these spectra can cause small shifts between the reference spectra and the unknown spectra, the comparison of the wavelengths obtained for the sodiumlike transitions with previous measurements indicates that such shifts, if present, were not significant. Owing to the spatial resolution resulting from the crossed mirror image and entrance slit, the lines from different spatial regions had a different appearance on the plate, and the reference lines were easily distinguished from the lines of the target elements. In addition, the lines from the hottest regions of the target plasma, such as the fluorine-

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Table 1. Wavelengths (in Å) and the Classification of Lines of Ions Isoelectronic with O I[a]

Transition	Y XXXII			Zr XXXIII			Nb XXXIV		
	Int.	λ_{meas}	λ^b_{pred}	Int.	λ_{meas}	λ^b_{pred}	Int.	λ_{meas}	λ^b_{pred}
$2s^22p^4\,{}^3P_2$–$2s2p^5\,{}^1P_1$	1	34.583	34.57			32.36			30.28
${}^3P_2$ ${}^3P_1$	15	44.857	44.89	8	42.285	42.35	4	39.932	39.97
${}^1D_2$ ${}^1P_1$	25	46.054	46.06	20	43.633	43.65	8	41.378	41.35
${}^3P_0$ ${}^3P_1$	8	48.882	49.02	8	46.027	46.19			43.54
${}^3P_1$ ${}^3P_0$	10	49.067	49.05	15	46.293[c]	46.28	3	43.758	43.66
${}^3P_2$ ${}^3P_2$	25	50.085	50.08	25	47.219	47.23	20	44.572	44.53
${}^3P_1$ ${}^3P_1$	5	61.917	61.99	4	59.730	59.84			57.83
${}^3P_1$ ${}^3P_2$	10	72.356	72.33	4	70.048	70.07			67.90
$2s2p^5\,{}^1P_1$–$2p^6\,{}^1S_0$	7	63.640	63.76	10	61.374	61.55			59.50

[a] In separate experiments described in Ref. 7, the following two transitions in Sr XXXI were observed: $2s^22p^4\,{}^3P_2$–$2s2p^5\,{}^3P_2$ at 53.104 Å and $2s^22p^4\,{}^1D_2$–$2s2p^5\,{}^1P_1$ at 48.570 Å.
[b] Predicted wavelengths based on extrapolations from Edlén (Ref. 5).
[c] Blended with Si XI.

Table 2. Energy Levels of Ions Isoelectronic with O I (in cm^{-1})

Level	Y XXXII	Zr XXXIII	Nb XXXIV
$2s^22p^4\,{}^3P_2$	0	0	0
${}^3P_0$	183 600	192 300	
${}^3P_1$	614 400	690 500	772 900 + y
${}^1D_2$	720 200	797 400 + x	884 600 + x
$2s2p^5$ ${}^3P_2$	1 996 600	2 117 800	2 243 600
${}^3P_1$	2 229 300	2 364 900	2 504 300
${}^3P_0$	2 652 400	2 850 600	3 058 200 + y
${}^1P_1$	2 891 600	3 089 200 + x	3 301 300 + x
$2p^6$ ${}^1S_0$	4 462 900	4 718 600 + x	

Table 3. Predicted Wavelengths of Magnetic-Dipole Transitions (in Å)

Transition	Y XXXII	Zr XXXIII	Nb XXXIV
$2s^22p^4\,{}^3P_2$–$2s^22p^4\,{}^1D_2$	138.9 ± 0.2	125.4 ± 0.5	113.0 ± 0.5
${}^3P_2$ ${}^3P_1$	162.8 ± 0.2	144.8 ± 0.2	129.4 ± 0.5
${}^3P_0$ ${}^3P_1$	232.1 ± 0.3	202.0 ± 0.3	
${}^3P_1$ ${}^1D_2$	945 ± 5	935 ± 15	895 ± 25

like and oxygenlike transitions, had a slight curvature across the plate, while the cooler sodiumlike and magnesiumlike lines were straight across the plate. All the fluorinelike and oxygenlike lines had the same characteristic appearance, which facilitated their identification. The position of each of these curved lines was measured at a point midway between the top and bottom of the line.

DISCUSSION

The wavelengths, intensities, and classifications of the identified lines of the oxygenlike ions Y XXXII, Zr XXXIII, and Nb XXXIV are listed in Table 1. The estimated accuracy of these measured wavelengths is 0.015 Å. The intensities are visual estimates of photographic plate darkening. Also listed in Table 1 are the wavelengths predicted with the semiempirical isoelectronic formulas of Edlén.[5] For the elements between krypton and molybdenum, these formulas use wavelengths interpolated from the Dirac–Fock calculations of Cheng *et al.*[6] The differences between the measured and predicted wavelengths in Table 1 are larger than was found[2] for the lower-Z ions (Z = 33–35). This is understandable, because the predicted values for the present ions represent a further extrapolation from the last experimental value used in Edlén's fit, Z = 32. The differences between the currently measured and predicted wavelengths are qualitatively consistent with the results for the lower-Z ions.[2] For example, the largest differences between the measured and predicted wavelengths occur for the $2s^22p^4\,{}^3P_0$–$2s2p^5\,{}^3P_1$ and $2s2p^5\,{}^1P_1$–$2p^6\,{}^1S_0$ transitions, and the measured wavelengths for these two transitions are lower than the predicted wavelengths.

The energy levels that are derived from the measured wavelengths are listed in Table 2, and the uncertainty in these energy levels is estimated to be 500 cm^{-1}. For levels not connected to the ground state by observed transitions, the energies are based on the predicted energies of the $2s^22p^4$ levels. These energies are noted with $+x$ or $+y$, and the uncertainty in these values is approximately 2000 cm^{-1}.

The wavelengths of the magnetic-dipole transitions within the $2s^22p^4$ ground configurations of Y XXXII, Zr XXXIII, and Nb XXXIV are listed in Table 3. To our knowledge, none of these transitions has been identified in tokamak spectra.

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