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XUV EMISSION FEATURES FROM THE LIVERMORE SOFT X-RAY LASER EXPERIMENTS(a)

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Abstract. - The measured wavelengths in the soft x-ray region for 3p to 3s and 3d to 3p transitions in neon-, sodium-, and magnesium-like selenium are presented. The experimental results for the neon-like ions are compared to theoretical wavelength values and with values extrapolated along the isoelectronic sequence. The ions were contained in a plasma heated in a line-focus of a Nd-glass laser. The measurements were made with a time-gated microchannel-plate-intensified grazing incidence spectrograph.

Experiments at the Lawrence Livermore National Laboratory have successfully produced amplified stimulated emission in neon-like ions of selenium, yttrium, and molybdenum contained in plasmas heated in the line focus of Nd-glass lasers.^{1,2} As an integral part of these experiments, there have been measurements, in the soft x-ray region, of the spectrum produced by transitions between the n=3 states, and also of the x-ray spectra due to the n=3 to n=2 transitions. As a part of this effort, we have identified and measured the wavelengths of the n=3 to n=3 transitions in neon-, sodium-, and magnesium-like ions of Se, Y, and Mo. We present here the measured values for the neon-, sodium-, and magnesium-like transitions in selenium.

Measurements in the soft x-ray region were obtained with two time-gated microchannel-plate-intensified grazing incidence spectrographs, one positioned to look along the plasma column axis and the other at an angle to it. Time gating is accomplished by sub-200ps switching of the microchannel-plate bias voltage in a microstrip geometry.¹ The dispersion of the instrument was calibrated by multiple high-resolution exposures of known spectra features of OIV, OV, NIV, and AlIV from a miniature Z-pinch. Non-linear least-squares fitting was used to determine line positions reported here to $\pm 0.01\text{\AA}$.

Including data taken in 1984, around 200 spectra have been digitized. Figure 1 shows a good resolution spectra taken from a 1 centimeter column of selenium plasma. Under lasing conditions, the on-axis spectra obtained from targets of two centimeters and longer are dominated by five $2s^2 2p^3 3p - 2s^2 2p^3 3s$ lasing

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Soft X-Ray Selenium Spectrum

Fig. 1. On axis spectrum of 1 centimeter column of selenium plasma taken with the McPigs time gated spectrometer. The feature at 173 Å is due to oxygen. The other features are due to magnesium-, sodium-, neon- and fluorine-like selenium.

lines.¹ Spontaneous emission lines coming from neon-, sodium-, and magnesium-like ions are observed in the off-axis spectra and as a component of the on-axis spectra. A small number of fluorine-like lines have also been tentatively identified in the selenium spectrum. A listing of the sodium-like selenium lines are given in table 1 and compared with other measurements and isoelectronic fits to the line positions.

The identification of most of the expected neon-like emission lines has been assured by carrying out relativistic multiconfiguration Hartree-Fock calculations and extrapolating the small systematic differences between theory and measurements at lower atomic numbers (Z's from 14 through 28) to the ions of current interest. The difference between the calculated and measured transition energies have been fit to the form:

$$\Delta E = A + B/(Z - Q).$$

There is excellent agreement between the extrapolated line positions and those measured. The present measurements in Se, Y, and Mo and other recent measurements in Ni and Cu⁷, Cu and Ge⁸, and Sr⁹ extend the range of Z over which the neon-like n=3 to 3 spectra have been observed.

Table 1. Sodium-like selenium wavelengths in Angstroms.

	Isoelectronic fits		Experimental values		
	Ref. 3	Ref. 4	Ref. 5	Ref. 6	present experiment
3p1/2 - 3d3/2	156.442	156.451	156.468	156.485	156.46
3p3/2 - 3d5/2	174.076	174.101	174.118	174.124	174.10
3p3/2 - 3d3/2	178.591	178.611	178.643	178.622	178.64
3s1/2 - 3p3/2	200.992	201.019	201.07	201.060	201.08
3s1/2 - 3p1/2	239.088	239.124	(239.23)	239.161	239.22

Two factors, in addition to wavelength position, have been taken into account in making the line assignments. We have compared the line strengths with theoretical predictions for the intensities and the systematic variation of the intensities of lines from the same ionic charge with changing plasma conditions. Other than the lasing lines and those originating from states having allowed x-ray transitions to the ground state, the strengths of the spontaneous emission lines follow roughly the gf value of the corresponding transitions. The systematic variation of the line intensities with plasma conditions allows the separation of lines from different ionic charge and the identification of the neon-like lines with 2s holes for which relatively little previous data exist.

The present ab initio calculations use the relativistic multiconfiguration Hartree-Fock code by Grant and his coworkers.¹⁰ The energy values for most of the levels are insensitive to the basis states used in the calculation. The J=0 even states, though, show variations around 1.5eV with different choices of basis states. We have not yet obtained convergence for a term-specific optimal level

Table 2. Wavelengths in Angstroms for observed transitions of neon-like selenium. States are labeled by major jj components, the vacancy in the n=2 shell is listed first. The lasing transitions are marked by a * and completely dominate the spectra for plasma columns of 3 centimeters or greater. Lines marked by a x are predicted to be weakly amplified and in some shots show strengths larger than those predicted by gf values.

state #'s	lower state		upper state	experiment	extrapolated	ab initio
	vac.	J	vac.	J		
x 3 15	2p3/2 3s1/2	1	2p1/2 3p1/2	0	113.4	113.14
6 20	2p3/2 3p1/2	1	2p3/2 3d5/2	2	161.73	161.65
7 21	2p3/2 3p1/2	2	2p3/2 3d3/2	2	162.29	161.92
12 24	2p1/2 3p1/2	1	2p1/2 3d3/2	2	167.58	167.33
x 3 11	2p3/2 3s1/2	1	2p3/2 3p3/2	0	168.67 ?	168.67
7 19	2p3/2 3p1/2	2	2p3/2 3d3/2	3	169.29	168.86
6 17	2p3/2 3p1/2	1	2p3/2 3d3/2	1	170.06	169.68
x 31 35	2s1/2 3p1/2	1	2s1/2 3d3/2	2	173.62	173.14
8 22	2p3/2 3p3/2	3	2p3/2 3d5/2	3	176.22	175.82
x 33 37	2s1/2 3p3/2	1	2s1/2 3d5/2	2	181.95	180.79
* 5 15	2p1/2 3s1/2	1	2p1/2 3p1/2	0	182.43	181.77 a
9 21	2p3/2 3p3/2	1	2p3/2 3d3/2	2	184.31	183.93
10 22	2p3/2 3p3/2	2	2p3/2 3d5/2	3	187.96	187.43
14 26	2p1/2 3p3/2	2	2p1/2 3d5/2	3	188.37	188.33
13 25	2p1/2 3p3/2	1	2p1/2 3d5/2	2	188.96 b	189.00
8 19	2p3/2 3p3/2	3	2p3/2 3d3/2	3		191.44
8 18	2p3/2 3p3/2	3	2p3/2 3d5/2	4	191.50	191.50
2 10	2p3/2 3s1/2	2	2p3/2 3p3/2	2	196.92 b?	196.71
10 20	2p3/2 3p3/2	2	2p3/2 3d5/2	2	204.33	204.42
* 3 10	2p3/2 3s1/2	1	2p3/2 3p3/2	2	206.38	206.25
4 13	2p1/2 3s1/2	0	2p1/2 3p3/2	1	208.18 ?	208.02
* 5 14	2p1/2 3s1/2	1	2p1/2 3p3/2	2	209.78	209.56
2 8	2p3/2 3s1/2	2	2p3/2 3p3/2	3	211.64	211.47
* 3 9	2p3/2 3s1/2	1	2p3/2 3p3/2	1	220.28	220.07
* 3 7	2p3/2 3s1/2	1	2p3/2 3p1/2	2	262.94	262.53

a) Using only the data for Z=26 and below. A fit, excluding the present Se data, but including that for Mo and those for Cu and Ge from ref. 9 gives a value of 182.44.

b) blended.

calculation for the $2p^{5/2} 3p^{1/2}$ state. We here follow Cogordan and coworkers¹¹ and used the average-level option for the $J=0$ even-parity excited states. The extrapolated energy values are insensitive to the ab initio data set.

Table 3 presents the wavelengths of the identified magnesium-like emission lines. The theoretical values are those from the RAC code written by one of the authors (JHS) which carries out a relativistic configuration-interaction calculation using basis states from an average-configuration Hartree-Fock calculation.

Results for the yttrium and molybdenum spectra will be given in the future.

Table 3. Magnesium-like selenium wavelengths in Angstroms.

	J_1	J_2	ab initio RAC code	previous exp. ref. 12	this experiment
3s3p-3s3d	0	1	139.7	140.85 a	
	1	2	142.3	143.36 a	143.12
several lines predicted in the region					144.14 146.90 147.64
3p ² -3p3d	1	2	151.2		151.70
3s3p-3s3d	2	3	153.1	154.04	154.22
	1	2	157.0	158.86	158.98
3p ² -3p3d	2	3	160.4		161.4
3p3s-3d ²	3	4	170.0		169.90 b
3s ² -3s3p	0	2	174.6	175.92	176.07 b
	2	3	202.0		203.88

a Calculated values.

b resolvable blend with neon-like lines

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