Spectrum of sodiumlike selenium: Se XXIV

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Received October 15, 1985; accepted December 12, 1985

High-resolution spectra of Se XXIV have been obtained with a 3-m grazing-incidence spectrograph. Thin plastic foils coated with selenium were irradiated with four or eight beams of the OMEGA laser in a line-focus configuration. Spectrograms were obtained by viewing the plasma axially. Prominent in the spectra were the $3s$–$3p$ and $3p$–$3d$ transitions in the 150–240-Å region and the transitions nl–$(n+1)l'$ with $n = 3, 4$ in the 24–80-Å region. We also present the energy levels and ionization limit derived from the measured wavelengths.

INTRODUCTION

In a series of experiments performed at the University of Rochester's OMEGA laser facility, thin plastic foils coated with selenium were irradiated by four or eight laser beams in a line-focus configuration.[1] The intensity of the C VI 182-Å transition increased anomalously with the plasma length, and this was consistent with a gain of 3 cm^{-1}. Gain on selenium transitions at 206.3 and 209.6 Å had been previously observed using similar targets at the Novette laser facility,[2,3] but the diagnostics and irradiation conditions used in the present experiments differed from those used in the Novette experiments, and we observed no evidence for gain on these selenium transitions.

The spectra were recorded by a 3-m grazing-incidence spectrograph that viewed the plasma from a position on the axis of the linear plasma. The selenium spectra from the line-focus plasma are of much higher quality than the spectra from point-focus plasmas that were recorded by the same spectrograph.[4,5] The narrow line profiles on the spectra from the line-focus plasma are probably a result of the restriction of the ion expansion velocities parallel to the axis.

In this paper, we report the measurement of the wavelengths of transitions in sodiumlike Se XXIV. We also present the energy levels derived from the measured wavelengths and the predicted ionization limit for Se XXIV.

EXPERIMENTAL TECHNIQUE

The selenium targets were composed of a layer of pure selenium 750 Å thick supported by a 1000-Å-thick Formvar plastic foil. This combination was mounted on an aluminum frame that was machined to permit simultaneous laser illumination of both the selenium and the Formvar sides. A small groove was machined to permit a better end view of the plasma by the spectrograph. The selenium side of the target was unobscured, whereas plasma on the Formvar side was obscured whenever it extended more than 200 μm from the target. Each OMEGA laser beam was focused into a line approximately 1.7 mm long and 100 μm wide by a cylindrical lens. The individual foci were precisely positioned to produce the desired length of plasma. Four beams were used for the 1.7- and 3.4-mm plasmas, and all eight available beams were used for the 6.8- and 13.6-mm plasmas.[1]

Each laser beam was frequency tripled (351 nm) and provided approximately 70 J of energy in a 600-psec pulse. Approximately 30% of the incident energy was absorbed by the target. The energy density of the laser illumination varied from 1.6×10^5 J/cm^2 for the 1.7-mm plasma to 4×10^4 J/cm^2 for the 13.6-mm plasma. The relative intensities of some of the spectral lines varied with the energy deposition, and this was useful in identifying the spectral lines from the highly excited levels. The 3.4-mm plasma yielded the best-developed spectrogram for the species reported here.

A 3-m grazing-incidence spectrograph[6] with a 1200-line/mm grating was used to record the spectra. A beryllium cylindrical mirror was placed 0.5 m in front of the slit, and the curvature was adjusted by bending until the plasma formed a line image that was crossed at an angle of 1.2° with the spectrograph slit. The grating–slit–cylindrical mirror arrangement was carefully adjusted so that the axis of the source (ideally a cylindrical plasma 100 μm in diameter and varying from 1.7 to 13.6 mm in length) was on the optical axis. A He–Ne laser was used as a reference beam to align the spectrograph and subsequently to align the targets.

With this alignment, the hottest part of the plasma illuminated the center of the photographic plate, and the cooler parts illuminated the margins. The appearance of the spectral lines on the plates could be used to determine qualitatively the selenium ionization stages and to identify the cooler impurity lines from aluminum, carbon, and oxygen.

Spectra were recorded on Kodak Type 101 spectroscopic plates and developed in D-19 developer. Approximately 76 cm of plate could be exposed in the instrument, and two

0740-3224/86/050701-03$02.00

plates were used. Three shots from the OMEGA laser were sufficient to produce well-exposed spectrograms when a 10-μm entrance slit width was used.

The spectrograms were measured with a Grant comparator and reduced to wavelengths by least-squares fitting to known impurity lines (mostly aluminum lines from material ablated from the target holder). The aluminum lines were emitted from a different part of the plasma from that for the selenium lines, and this introduced the possibility of small indeterminate shifts. Since the plasma was viewed axially and most plasma motions were perpendicular to the line of sight of the spectrometer, the Doppler shifts are expected to be small. In general, the accuracy of the wavelengths is better than 0.01 Å, with somewhat lower accuracy near 100 Å where the two plates join and also at 25–30 Å where no independent wavelength standards were found. Spectrograms from plasmas with four lengths (1.7, 3.4, 6.8, and 13.6 mm) were measured, and the resulting wavelengths were averaged. In addition, many strong lines appeared in two or more orders, and the additional orders were used to improve the accuracy of the final wavelengths. Where possible, the use of blended lines was avoided in the determination of the final wavelengths and energy levels.

RESULTS

Excellent theoretical[7] and semiempirical[8] predictions treat the sodiumlike ions through Mo XXXII and form the basis of the present analysis. In addition, earlier experimental data on laser-produced spectra[9,10] provide wavelengths for some of the observed transitions. However, the present results represent a significant improvement in extent and accuracy.

The measured wavelengths are presented in Table 1. Where comparisons can be made, the wavelengths measured at present for the $3s$–$3p$ and $3p$–$3d$ transitions are in good overall agreement with the measurements of Kononov *et al.*[10] Our wavelengths are significantly larger than the recommendations of Edlén[8] and the measurements of Fawcett and Hayes.[9] For the $3s$–$4p$, $3p$–$4d$, $3p$–$4s$, and $3d$–$4f$ transitions, our wavelengths are in good agreement with the measurements of Fawcett and Hayes.[9] Previous measurements for the other transitions listed in Table 1 do not exist. The energy levels derived from the measured wavelengths are listed in Table 2.

The approximate relative intensities of the transitions are listed in the second column in Table 1. The unusually high intensity of the $4d$–$5f$ and $4f$–$5g$ transitions is attributed to the favored population of the high l levels in the recombining selenium plasma.

For levels with $l > 2$, the polarization formulas have been shown[8] to be an accurate means of predicting energy levels and ionization limits for the Na I isoelectronic sequence. Using the fitting constants from Ref. 8, the polarization energy of the core (Δ_p) is presented in Table 3. The ionization energy T is the sum of the core polarization energy and the ionization energy calculated from the relativistic hydrogenic expression (T_H). The ionization limit E_l is obtained by adding the excitation energy E derived from the measured wavelengths:

$$E_l = \Delta_p + T_H + E. \quad (1)$$

Table 1. Wavelengths (in Angstroms) for Transitions in Se XXIV

Transition	Int.	Measured			Calculated	
		Present[a]	Ref. 9	Ref. 10	Ref. 8	Ref. 9
$3s$–$3p$						
$^2S_{1/2}$–$^2P_{3/2}$	50	201.060		201.07	200.992	200.95
$^2S_{1/2}$–$^2P_{1/2}$	20	239.161			239.088	239.10
$3p$–$3d$						
$^2P_{1/2}$–$^2D_{3/2}$	100	156.485	156.29	156.468	156.442	156.31
$^2P_{3/2}$–$^2D_{5/2}$	75	174.124	173.96	174.118	174.076	173.96
$^2P_{3/2}$–$^2D_{3/2}$	30	178.625		178.643	178.591	
$3s$–$4p$						
$^2S_{1/2}$–$^2P_{3/2}$	6	24.539	24.53			
$^2S_{1/2}$–$^2P_{1/2}$	5	24.731	24.73			
$3p$–$4d$						
$^2P_{1/2}$–$^2D_{3/2}$	10	25.859	25.83			
$^2P_{3/2}$–$^2D_{5/2}$	10	26.348	26.35			
$^2P_{3/2}$–$^2D_{3/2}$	6	26.398				
$3p$–$4s$						
$^2P_{1/2}$–$^2S_{1/2}$	3	28.909	28.907			
$^2P_{3/2}$–$^2S_{1/2}$	4	29.595	29.596			
$3d$–$4f$						
$^2D_{3/2}$–$^2F_{5/2}$	12	29.964	29.960			
$^2D_{5/2}$–$^2F_{7/2}$	15	30.074D	30.068			
$^2D_{5/2}$–$^2F_{5/2}$		30.095P				
$3d$–$4p$						
$^2D_{3/2}$–$^2P_{3/2}$		33.135P				
$^2D_{5/2}$–$^2P_{3/2}$		33.295P				
$^2D_{3/2}$–$^2P_{1/2}$		33.486P				
$4s$–$5p$						
$^2S_{1/2}$–$^2P_{3/2}$	3	55.894				
$^2S_{1/2}$–$^2P_{1/2}$	3	56.368D				
$4p$–$5d$						
$^2P_{1/2}$–$^2D_{3/2}$	5	58.126D				
$^2P_{3/2}$–$^2D_{5/2}$	10	59.088				
$^2P_{3/2}$–$^2D_{3/2}$		59.215P				
$4d$–$5f$						
$^2D_{3/2}$–$^2F_{5/2}$	20	65.188				
$^2D_{5/2}$–$^2F_{7/2}$	25	65.406				
$^2D_{5/2}$–$^2F_{5/2}$		65.501P				
$4p$–$5s$						
$^2P_{1/2}$–$^2S_{1/2}$	2	65.54				
$^2P_{3/2}$–$^2S_{1/2}$	1	66.93				
$4f$–$5g$						
$^2F_{5/2}$–$^2G_{7/2}$	30	69.731				
$^2F_{7/2}$–$^2G_{9/2}$	35	69.818				
$^2F_{7/2}$–$^2G_{7/2}$		69.842P				
$4d$–$5p$						
$^2D_{3/2}$–$^2P_{3/2}$		72.438P				
$^2D_{5/2}$–$^2P_{3/2}$		72.824P				
$^2D_{3/2}$–$^2P_{1/2}$		73.236P				
$4f$–$5d$						
$^2F_{5/2}$–$^2D_{5/2}$		72.833P				
$^2F_{7/2}$–$^2D_{5/2}$		72.953P				
$^2F_{5/2}$–$^2D_{3/2}$		73.026P				

[a] D, diffuse; P, predicted.

Table 2. Energy Levels (in Inverse Centimeters) for Se XXIV

Level	Energy
$3s\ ^2S_{1/2}$	0
$3p\ ^2P_{1/2}$	418 128
$^2P_{3/2}$	497 364
$3d\ ^2D_{3/2}$	1 057 180
$^2D_{5/2}$	1 071 667
$4s\ ^2S_{1/2}$	3 876 790
$4p\ ^2P_{1/2}$	4 043 510
$^2P_{3/2}$	4 075 150
$4d\ ^2D_{3/2}$	4 285 390
$^2D_{5/2}$	4 292 720
$4f\ ^2F_{5/2}$	4 394 520
$^2F_{7/2}$	4 396 800
$5s\ ^2S_{1/2}$	5 569 270
$5p\ ^2P_{1/2}$	5 650 840
$^2P_{3/2}$	5 665 890
$5d\ ^2D_{3/2}$	5 763 910
$^2D_{5/2}$	5 767 540
$5f\ ^2F_{5/2}$	5 819 420
$^2F_{7/2}$	5 821 630
$5g\ ^2G_{7/2}$	5 828 610
$^2G_{9/2}$	5 829 090

Table 3. Ionization Energies (in Inverse Centimeters) for Se XXIV[a]

nl	j	$\Delta_p(n,l)$	$T_H(n,j)$	$T(n,j)$	$E(n,j)$	E_l
$4f$		9960				
	5/2		3 954 934	3 964 894	4 394 520	8 359 410
	7/2		3 952 410	3 962 369	4 396 800	8 359 170
$5f$		7045				
	5/2		2 531 174	2 538 219	5 819 420	8 357 640
	7/2		2 529 881	2 536 927	5 821 630	8 358 560
$5g$		516				
	7/2		2 529 881	2 530 397	5 828 610	8 359 010
	9/2		2 529 106	2 529 622	5 829 090	8 358 710

[a] The adopted value for the ionization limit is 8 358 700 ± 1000 cm^{-1}.

As shown in Table 3, the ionization limits (8 359 410 and 8 359 170 cm^{-1}) derived from the $4f$ levels are in excellent agreement with Edlén's value of 8 359 375 cm^{-1}. The ionization limits derived from the $5f$ and $5g$ levels are consistently smaller than Edlén's value. The largest difference occurs for the $5f$ levels, where the ionization limits are 850 and 1770 cm^{-1} smaller than Edlén's value. The energies of the $n = 5$ levels are based on two wavelength measurements, and the possible error in these energy levels is estimated to be 1000 cm^{-1}. Therefore the difference between the ionization limits derived from the $5f$ levels and Edlén's value may be significant. It is interesting to note that, in the case of Mo XXXII, the ionization limits derived from the $5f$ levels are an average of 4400 cm^{-1} smaller than the values derived from the $4f$ levels.[8] For $Z > 29$, the fitting constants (A and k in Ref. 8) are based primarily on the $4f$ levels, and it is possible that the application of these fitting constants to the $5f$ levels results in an underestimation of the polarization energy and the ionization limit. In the case of the $5g$ levels, the ionization limits presented in Table 3 are an average of 500 cm^{-1} smaller than Edlén's value, and this is comparable with the polarization energy (516 cm^{-1}) and is within the possible error in the energy levels derived from the measured wavelengths. Therefore we cannot draw conclusions concerning the applicability of the fitting constants to the $5g$ levels.

ACKNOWLEDGMENTS

The work performed at the Naval Research Laboratory was supported by the U.S. Department of Energy under contract DE-AI08-84DP40092/26. Research and materials were partially developed at the National Laser User's Facility at the University of Rochester's Laboratory for Laser Energetics, with financial support from the U.S. Department of Energy under contract DE-FC08-85DP40200.

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