Transitions in Na-like and Mg-like ions of In, Sb, I, and Cs

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The spectra of highly charged ions of the elements In, Sb, I, and Cs have been recorded by using a 3-m grazing-incidence spectrograph at the University of Rochester's Laboratory for Laser Energetics. Transitions in the Na I and Mg I isoelectronic sequences have been identified. Wavelengths in the range 7–100 Å were measured to an accuracy of ± 0.02 Å, and energy levels were derived from the measured wavelengths.

INTRODUCTION

Transitions in the Na I isoelectronic sequence were observed previously for the elements up to Ag ($Z = 47$) and for Sn ($Z = 50$), and wavelengths were predicted for the elements through Xe ($Z = 54$).[1] Transitions in the Mg I sequence were observed through Rh ($Z = 45$).[2] In this paper we report the observation of transitions in Na-like and Mg-like ions of the elements In, Sb, I, and Cs ($Z = 49$, 51, 53, and 55).

EXPERIMENT

The spectra were produced by irradiating spherical targets by using the frequency-tripled (0.351-nm) Nd:glass OMEGA laser at the University of Rochester's Laboratory for Laser Energetics.[3] The targets were solid polystyrene microspheres, 200 μm in diameter, and the targets were mounted on glass stalks. A coating of InSb or CsI approximately 0.5 μm thick was evaporated onto each microsphere and stalk. The 24 OMEGA laser beams were incident upon the microsphere in a spherically symmetric pattern. Each laser beam was focused with $f/3.7$ optics to a point-eight target radii beyond the center of the microsphere. This beam-and-focusing configuration provided the most uniform illumination of the target with an estimated 20% variance. Each beam delivered approximately 50 J in a pulse duration of 600 psec, and the average focused intensity at the target surface was 1.6×10^{15} W/cm^2.

The spectra were recorded by a 3-m grazing-incidence spectrograph fitted with a gold-coated replica grating having

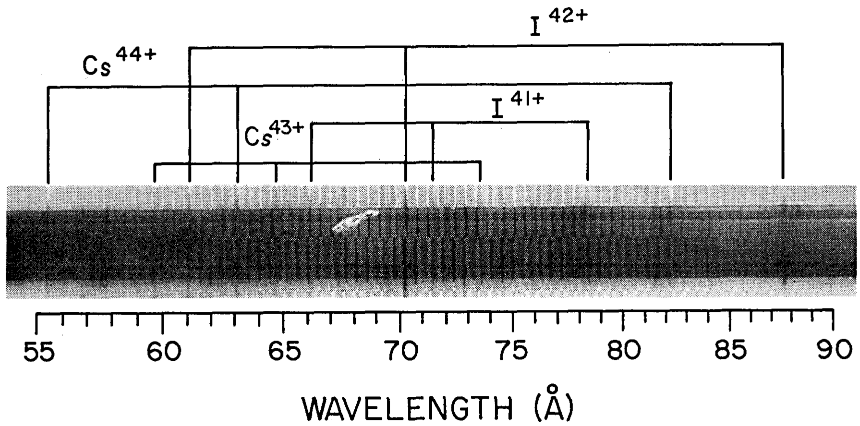

Fig. 1. The spectrum from the CsI target in the wavelength range 55–90 Å. Transitions in the Na-like and Mg-like ions of Cs and I are indicated. The dark horizontal regions at the top and the bottom of the spectrum are calibration spectra from a glass microballoon target that were superimposed upon the CsI spectrum by using a slotted aperture.

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Table 1. Wavelengths (in Angstroms) and Classifications of Spectral Lines for Na-like Ions

	In^{38+}				Sb^{40+}				I^{42+}				Cs^{44+}		
Transition	Intensity[a]	Measured	Predicted[b]	Calculated[c]	Intensity[a]	Measured	Predicted[b]	Calculated[c]	Intensity[a]	Measured	Predicted[b]	Calculated[c]	Intensity[a]	Measured	Calculated[c]
$3s\ ^2S_{1/2}$–$3p\ ^2P_{3/2}$	3	87.282	87.263	87.174	20	78.311	78.315	78.237	40	70.276	70.306	70.247	20	63.108	63.094
$3p\ ^2P_{1/2}$–$3d\ ^2D_{3/2}$	2	74.194	74.203	74.181	10	67.348	67.360	67.345	16	61.131	61.147	61.136	10	55.510	55.496
$3p\ ^2P_{3/2}$–$3d\ ^2D_{5/2}$	2	99.831	99.808	99.780	10	93.509	93.479	93.480	25	87.644	87.635	87.646	10	82.225	82.239
$3s\ ^2S_{1/2}$–$4p\ ^2P_{3/2}$	3	9.799		9.850	4	8.896		8.933				8.132			7.429
$3s\ ^2S_{1/2}$–$4p\ ^2P_{1/2}$	3	9.999		10.027	2	9.066		9.108				8.307			7.603
$3p\ ^2P_{1/2}$–$4s\ ^2S_{1/2}$				11.140	1	10.088		10.076				9.153			8.348
$3p\ ^2P_{3/2}$–$4s\ ^2S_{1/2}$	1	11.771		11.717	2	10.678		10.647				9.719			8.909
$3p\ ^2P_{1/2}$–$4d\ ^2D_{3/2}$	2	10.185		10.216	3	9.218		9.251				8.412			7.677
$3p\ ^2P_{3/2}$–$4d\ ^2D_{5/2}$	4	10.629		10.651	6	9.648		9.683				8.839			8.100
$3d\ ^2D_{3/2}$–$4f\ ^2F_{5/2}$	3	11.522	11.535	11.545	10	10.425	10.447	10.456	3	9.504	9.505	9.512	1	8.681	8.690
$3d\ ^2D_{5/2}$–$4f\ ^2F_{7/2}$	5	11.629	11.641	11.651	12	10.532	10.553	10.561	3	9.601	9.611	9.618	1	8.788	8.795
$4d\ ^2D_{3/2}$–$5f\ ^2F_{5/2}$				25.045				22.675				20.623			18.835
$4d\ ^2D_{5/2}$–$5f\ ^2F_{7/2}$				25.253				22.882				20.829			19.040
$4f\ ^2F_{5/2}$–$5g\ ^2G_{7/2}$				26.366	1	23.829		23.846				21.669			19.775
$4f\ ^2F_{7/2}$–$5g\ ^2G_{9/2}$	2	26.403		26.451	1	23.910		23.931				21.754	1	19.848	19.861

[a] Intensities based on visual estimates of plate darkening.
[b] Wavelengths predicted by Reader *et al.*[1]
[c] Wavelengths calculated by the present authors using Grant's program.[7,8]

Table 2. Wavelengths (in Angstroms) and Classification of Spectral Lines for Mg-like Ions

	In^{37+}				Sb^{39+}				I^{41+}				Cs^{43+}			
Transition	Intensity[a]	Measured	Predicted[b]	Calculated[c]	Intensity[a]	Measured	Predicted[b]	Calculated[c]	Intensity[a]	Measured	Predicted[b]	Calculated[c]	Intensity[a]	Measured	Predicted[b]	Calculated[c]
$3s^2\ ^1S_0$–$3s3p\ ^1P_1$	1	81.333	81.037	80.784	1	73.320	73.126	72.983	10	66.205	65.976	65.921	12	59.749	59.510	59.532
$3s3p\ ^3P_2$–$3s3d\ ^3D_3$			88.857	88.537	2	83.388	83.292	83.074	3	78.304	78.131	78.032	4	73.491	73.351	73.361
$3s3p\ ^1P_1$–$3s3d\ ^1D_2$	1	85.965	85.609	85.361	2	78.610	78.290	78.197	10	71.500	71.185	71.236	12	64.743	64.433	64.578

[a] Intensities based on visual estimates of plate darkening.
[b] Wavelengths predicted by Ivanova *et al.*[9]
[c] Wavelengths calculated by the present authors using Grant's program.[7,8]

Table 3. Energy Levels (in 10^3 cm^{-1}) for the Na-like Ions

Level	In^{38+} Measured	In^{38+} Calculated[a]	Sb^{40+} Measured	Sb^{40+} Calculated[a]	I^{42+} Measured	I^{42+} Calculated[a]	Cs^{44+} Measured	Cs^{44+} Calculated[a]
$3s\ ^2S_{1/2}$	0	0	0	0	0	0	0	0
$3p\ ^2P_{1/2}$	703.7[b]	705.1	744.8[b]	746.0	787.1[b]	787.6	829.8[b]	830.1
$3p\ ^2P_{3/2}$	1 145.7	1 147.1	1 277.0	1 278.2	1 423.0	1 423.5	1 584.6	1 584.9
$3d\ ^2D_{3/2}$	2 051.5	2 053.2	2 229.6	2 230.9	2 422.9	2 423.3	2 631.3	2 632.0
$3d\ ^2D_{5/2}$	2 147.4	2 149.3	2 346.4	2 347.9	2 563.9	2 564.5	2 800.8	2 800.9
$4s\ ^2S_{1/2}$	9 641.2	9 681.6	10 642	10 670		11 713		12 809
$4p\ ^2P_{1/2}$	10 001	9 972.9	11 030	10 979		12 039		13 153
$4p\ ^2P_{3/2}$	10 205	10 152	11 241	11 195		12 297		13 460
$4d\ ^2D_{3/2}$	10 522	10 494	11 593	11 555		12 675		13 857
$4d\ ^2D_{5/2}$	10 554	10 536	11 642	11 606		12 737		13 930
$4f\ ^2F_{5/2}$	10 731	10 715	11 822	11 795	12 945	12 936	14 151	14 139
$4f\ ^2F_{7/2}$	10 747	10 733	11 841	11 817	12 980	12 962	14 180	14 171
$5f\ ^2F_{5/2}$		14 487		15 965		17 524		19 166
$5f\ ^2F_{7/2}$		14 496		15 976		17 538		19 182
$5g\ ^2G_{7/2}$		14 508	16 018	15 989		17 551		19 196
$5g\ ^2G_{9/2}$	14 534	14 513	16 024	15 995		17 559	19 218	19 206

[a] Energies calculated by the present authors using Grant's program.[7,8]
[b] Energy based on the measured $3p\ ^2P_{3/2}$ energy and the calculated $3p\ ^2P_{1/2}$–$^2P_{3/2}$ splitting.

Table 4. Energy Levels (in 10^3 cm^{-1}) for the Mg-like Ions

Level	In^{37+} Measured	In^{37+} Predicted[a]	Sb^{39+} Measured[b]	Sb^{39+} Predicted[a]	I^{41+} Measured[b]	I^{41+} Predicted[a]	Cs^{43+} Measured[b]	Cs^{43+} Predicted[a]
$3s^2\ ^1S_0$	0	0	0	0	0	0	0	0
$3s3p\ ^3P_2$		1044.0	1169.7 + x	1169.8	1310.2 + x	1310.0	1466.9 + x	1466.6
$3s3p\ ^1P_1$	1229.5	1234.0	1363.9	1367.5	1510.5	1515.7	1673.7	1680.4
$3s3d\ ^3D_3$		2169.4	2368.9 + x	2370.4	2587.3 + x	2589.9	2827.6 + x	2829.9
$3s3d\ ^1D_2$	2392.8	2402.1	2636.0	2644.8	2909.1	2920.5	3218.2	3232.4

[a] Predicted energies of Ivanova *et al.*[9]
[b] The x's are the uncertainty in energies derived from Ref. 9.

1200 lines/mm.[4] The angle of incidence was 2°. The spectra in the range 6–100 Å were recorded using a grating blazed at 2°35′, and, for the 2° angle of incidence, this blaze angle corresponds to a wavelength of 60 Å. The spectra from 30 to 200 Å were recorded using a grating blazed at 4°7′, which corresponds to a wavelength of 127 Å.

A gold-coated cylindrical mirror was positioned 1.3 m from the target and 0.5 m in front of the entrance slit of the spectrograph.[5] The linear image formed by the mirror was focused on the entrance slit. The image was tilted by an angle of approximately 1° with respect to the entrance slit, and this arrangement resulted in the spatial resolution of the target plasma in one dimension.[6] The spectra were recorded on Kodak 101-05 photographic plates, and one or two laser shots produced a good exposure. The spectrum from the CsI target is shown in Fig. 1.

WAVELENGTHS AND ENERGY LEVELS

The wavelengths and classifications of the identified spectral lines are presented in Tables 1 and 2. Calibration spectra from glass microballoon targets were superimposed upon the spectra of the high-Z elements by using a slotted aperture. The calibration spectra included lines from O VIII, O VII, O VI, and Si XII. Lines from C VI were also observed, indicating that the high-intensity laser irradiation burned through the 0.5-μm high-Z coating to the plastic substrate. There was no significant wavelength shift between the carbon lines and the oxygen and silicon lines. The overall uncertainty in the measured wavelengths is estimated to be ±0.02 Å.

Also listed in Tables 1 and 2 are wavelengths calculated by using the multiconfiguration Dirac–Fock (MCDF) computer program developed by Grant *et al.*[7,8] The calculations included finite nuclear size and quantum electrodynamic and Breit corrections. The calculations were performed using the extended average level option. All of the Na-like levels with principal quantum number n = 3, 4, and 5 were included. For the Mg-like ions, the $3s^2$, $3s3p$, $3p^2$, $3s3d$, $3p3d$, and $3d^2$ configurations were included.

The predicted wavelengths for the Na I sequence listed in Table 1 are based on the differences between the observed and calculated wavelengths for lower-Z elements.[1] The predicted wavelengths for the Mg I sequence listed in Table 2 are based on model-potential calculations normalized to lower-Z observations.[9]

Listed in Tables 3 and 4 are the energy levels derived from the measured wavelengths. The estimated uncertainty in the energies of the n = 3 levels is ±400 cm^{-1}, and the estimated uncertainty in the energies of the n = 4 and n = 5 levels is ±20 000 cm^{-1}. Since the Na-like $3s\ ^2S_{1/2} - 3p\ ^2P_{1/2}$ transition was not observed, the splitting of the $3p\ ^2P_{1/2}$ and $^2P_{3/2}$

levels could not be determined accurately from the measurements. The calculated splitting was used in the determination of the energies of the higher levels. Since the splitting of the $^2P_{1/2}$ and $^2P_{3/2}$ levels is a relativistic effect, the uncertainty in the calculated splitting is expected to be less than the uncertainties in the level energies that are derived from the measured wavelengths.

In the case of the Mg-like ions, the singlet and triplet levels cannot be connected by using the present observations. The uncertainty in the energies of the triplet levels is indicated in Table 4 by x, and this uncertainty is estimated to be $\pm 1 \times 10^5$ cm^{-1}.

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