Transitions of the type $2s$–$2p$ in highly ionized Cu, Zn, Ga, and Ge

W. E. Behring

Laboratory for Solar Physics and Astrophysics, Goddard Space Flight Center, Greenbelt, Maryland 20771

J. F. Seely

E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, D.C. 20375

Samuel Goldsmith

Laboratory for Plasma and Fusion Energy Studies, University of Maryland, College Park, Maryland 20742

Leonard Cohen

Laboratory for Solar Physics and Astrophysics, Goddard Space Flight Center, Greenbelt, Maryland 20771

M. Richardson

Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623

U. Feldman

E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, D.C. 20375

Received June 25, 1984; accepted January 7, 1985

Transitions of the type $2s$–$2p$ in the F I, O I, N I, and C I isoelectronic sequences of copper, zinc, gallium, and germanium have been identified in the spectra from plasmas produced by the OMEGA laser system at the University of Rochester. The wavelengths are in the range 50 to 112 Å and are measured using silicon and oxygen lines as wavelength standards for gallium and using several lines from the F I, O I, and Na I isoelectronic sequences as wavelength standards for copper, zinc, and germanium. The energy levels that are determined from the measured wavelengths are also presented. Based on these measurements, the wavelengths for a number of magnetic-dipole transitions within the ground configurations of the F I, O I, and N I isoelectronic sequences are predicted.

INTRODUCTION

Transitions of the type $2s^22p^k$–$2s2p^{k+1}$ (where $k = 2, 3, 4, 5$) are prominent in the spectra obtained from astrophysical and laboratory plasmas. A number of lines from iron and nickel near 100 Å have been identified in the spectra of solar flares,[1] and transitons in Ge XXIV and Ge XXV have recently been identified in tokamak spectra.[2] Transitions in Zn XXII, Zn XXIII, Zn XXIV, Ge XXIV, and Ge XXV have been identified in spectra from laser-produced plasmas.[3] At low densities, the forbidden transitions between levels within the ground configuration of high-Z ions are intense. These transitions appear in the VUV and visible regions of the spectrum and are useful for the determination of a number of plasma parameters. By measuring the wavelengths of the allowed transitions that terminate on levels in the ground configuration, it is possible to predict the wavelengths of the forbidden transitions that occur within the ground configuration.

In this paper, we report the observation of spectral lines in the F I, O I, N I, and C I isoelectronic sequences of copper, zinc, gallium, and germanium. The plasma was produced by the spherical irradiation of solid targets using six frequency-tripled beams[4] from the OMEGA laser system at the University of Rochester.[5] The wavelengths were recorded using a 3-m grazing-incidence spectrograph, and the wavelengths were determined relative to several previously observed lines in the F I, O I, and Na I sequences. There is good overall consistency with the wavelengths recommended by Edlén[6] for the F I and O I sequences and with the wavelengths measured by Kononov[7] for the Na I sequence. Most of the observed transitions in the N I and C I sequences represent new identifications, and a complete set of energy levels for the $2s2p^4$ configuration of the N-like ions Cu XXIII, Zn XXIV, Ga XXV, and Ge XXVI is presented. The energy levels for the F I, O I, and C I sequences are also presented.

EXPERIMENT

The targets were spherically irradiated with an approximately cubic array of six beams from the OMEGA laser system. The laser was frequency tripled (351 nm), and, for each laser shot, the energy incident on target was between 200 and 300 J with a pulse duration of 600 to 700 psec. Each laser beam was focused by an $f/3.7$ lens to a point a distance of 4 target radii beyond the center of the target. The average intensity of

0740-3224/85/060886-05$02.00

Table 1. Classifications of Lines Isoelectronic with F I (in angstroms)[a]

Transition	Cu XXI	Zn XXII	Int.	Ga XXIII	Int.	Ge XXIV	Int.
$2s^22p^5$–$2s2p^6$							
$^2P_{3/2}$–$^2S_{1/2}$	78.390 B	73.941 A,B	20	69.782 B	40	65.893 A,B	10
$^2P_{1/2}$–$^2S_{1/2}$	90.354 B	86.538 A,B	13	83.013 B	25	79.736 A,B	7

[a] A indicates transitions previously identified by Behring et al.[3]; B indicates transitions previously identified by Kononov et al.[9]

Table 2. Classifications of Lines Isoelectronic with O I (in angstroms)[a]

Transition	Cu XXII	Zn XXIII	Int.	Ga XXIV	Int.	Ge XXV	Int.
$2s^22p^4$–$2s2p^5$							
$^3P_2$–$^1P_1$	[65.43]	61.491 B	6	57.779	6	[54.27]	
$^1D_2$–$^1P_1$	77.521 B	73.583 A,B	17	69.862	30	66.364 A	9
$^3P_2$–$^3P_1$	83.170 B	77.948 A,B	9	73.107	15	68.616 A	5
$^3P_1$–$^3P_0$	[88.38]	83.228 A,B	7	78.385	12	[73.88]	
$^3P_2$–$^3P_2$	90.257 B	85.022 A,B	15	80.110 bl	30	75.514 A	4
$^3P_0$–$^3P_1$	[90.85]	85.283 A,B	7	80.110 bl	30	75.177 A	2
$^1S_0$–$^1P_1$	[93.30]	89.754 A,B	5	86.552	4	83.590	2
$^3P_1$–$^3P_1$	[95.22]	90.582 bl,A,B	4	86.316	4	82.385	2
$^3P_1$–$^3P_2$	[104.61]	100.303 B	6	96.255	4	[92.53]	
$2s2p^5$–$2p^6$							
$^1P_1$–$^1S_0$	[98.18]	93.347	6	88.900	2	84.826	3

[a] A indicates transitions previously identified by Behring et al.[3]; B indicates transitions previously identified by Kononov et al.[9]; bl, blend; data in brackets, interpolated.

Table 3. Classification of Lines Isoelectronic with N I (in angstroms)[a]

Transition	Cu XXIII	Zn XXIV	Int.	Ga XXV	Int.	Ge XXVI	Int.
$2s^22p^3$–$2s2p^4$							
$^4S_{3/2}$–$^2P_{3/2}$	[67.31]	63.346	4	[59.56]		[55.95]	
$^2D_{3/2}$–$^2P_{3/2}$	[76.06]	71.917	0	68.009	1	[64.36]	
$^2D_{3/2}$–$^2S_{1/2}$	79.636 bl	75.290	8	71.232 bl	2	67.433	1
$^2D_{5/2}$–$^2P_{3/2}$	79.636 bl,B	75.499 A	13	71.561	6	67.836	3
$^2P_{3/2}$–$^2P_{1/2}$	83.335 B	78.957 A	9	74.866	8	70.990	2
$^2P_{1/2}$–$^2P_{3/2}$	[86.38]	81.866	3	77.54	5	[73.48]	
$^2P_{1/2}$–$^2S_{1/2}$	91.028	86.266	7	81.776	4	77.512 bl	2
$^2D_{3/2}$–$^2D_{3/2}$	92.695 B	87.686 B	9	[83.05]		78.698	2
$^2D_{5/2}$–$^2D_{5/2}$	94.847 B	89.474 A,B	8	84.401	11	79.637	2
$^4S_{3/2}$–$^4P_{1/2}$	96.457	90.046	4	84.110	5	[74.49]	
$^4S_{3/2}$–$^4P_{3/2}$	98.892	92.182 bl	6	85.910	2	80.079	2
$^4S_{3/2}$–$^4P_{5/2}$	[111.05]	104.537	3	98.333 bl	6	92.624 bl	3
$2s2p^4$–$2p^5$							
$^2D_{3/2}$–$^2P_{3/2}$	[93.63]	89.013	4	84.713 bl	4	[80.74]	
$^2D_{5/2}$–$^2P_{3/2}$	96.762 bl	92.617	5	88.749	6	85.181	1
$^2P_{1/2}$–$^2P_{1/2}$	[118.11]	112.37 bl	4				

[a] A indicates transitions previously identified by Behring et al.[3]; B indicates transitions previously identified by Kononov et al.[9]; bl, blend; data in brackets, interpolated.

Table 4. Classification of Lines Isoelectronic with C I (in angstroms)[a]

Transition	Cu XXIV	Zn XXV	Int.	Ga XXVI	Int.	Ge XXVII	Int.
$2s^22p^2$–$2s2p^3$							
$^3P_2$–$^1D_2$		77.111	2				
$^3P_1$–$^3S_1$	83.052	78.714	2	74.60	6	[70.73]	
$^3P_2$–$^3S_1$	87.107	82.640	7	78.385	12	74.301	1
$^3P_2$–$^3P_2$	99.206	92.85	5	86.946	2	81.370	0
$^3P_0$–$^3D_1$	[104.41]	97.449	3	91.063	6	[85.25]	

[a] bl, blend; data in brackets, interpolated.

351-nm light at the target surface was 1×10^{14} W/cm^2. The overall absorption of laser energy by the target was 88 to 92%. At the irradiation intensities used, the absorption process for the 351-nm radiation was almost entirely inverse bremsstrahlung, with a very small fraction ($<10^{-4}$) of the absorbed energy going to superthermal electrons.

In the case of zinc, the targets were solid fragments of pure zinc and were roughly spherical in shape with an average diameter of 450 μm. The copper, gallium, and germanium targets were coated-glass microballoons. The average diameter of the microballoons was 350 μm, and the thickness of the glass shell was 1 μm. The thickness of the copper, gallium, and germanium coatings was 3 to 10 μm. Additional gallium spectra were collected using crystals of GaAs approximately 400 μm in size.

The spectral data were accumulated over six shots for each of the target materials. The spectra were recorded by a 3-m grazing-incidence (88°) spectrograph that has been described in detail in Ref. 8. The spectrograph was fitted with a 600-line/mm gold-coated Bausch & Lomb replica grating, and spectral lines were observed in the range 30 to 260 Å.

A number of spectral lines from Cu XXI and Cu XXII were observed in first, second, and third order, and these lines were used as references[6] to establish the wavelength scale for the copper plate. The accuracy of the copper wavelength measurements is estimated to be better than 0.02 Å.

The gallium wavelengths were determined by comparison of line positions in the second, third, fourth and fifth orders with the positions of lines from oxygen and silicon appearing near the edge of the plate. These probably originated from the glass stalk holding the microballoon. These averaged wavelengths were then used to adjust the first- and second-

Table 5. Energy Levels Isoelectronic with F I (in inverse centimeters)

Level	Cu XXI	Zn XXII	Ga XXIII	Ge XXIV
$2s^22p^5\,{}^2P_{3/2}$	0	0	0	0
${}^2P_{1/2}$	168 920	196 870	228 400	263 470
$2s\,2p^6\,{}^2S_{1/2}$	1 275 670	1 352 430	1 433 030	1 517 610

Table 6. Energy Levels Isoelectronic with O I (in inverse centimeters)

Level	Cu XXII	Zn XXIII	Ga XXIV	Ge XXV
$2s^22p^4\,{}^3P_2$	0	0	0	0
${}^3P_0$		110 340	119 58	127 190
${}^3P_1$		179 060	209 330	243 570
${}^1D_2$	238 280 + z	267 120	299 410	335 890 + z
${}^1S_0$		512 070	575 490	646 420 + z
$2s2p^5\,{}^3P_2$	1 107 950	1 176 110	1 248 280	1 324 260
${}^3P_1$	1 202 360	1 282 970	1 367 860	1 457 390
${}^3P_0$		1 380 580	1 485 080	
${}^1P_1$	1 528 250 + z	1 626 230	1 730 860	1 842 730 + z
$2p^6\,{}^1S_0$		2 697 570	2 855 840	3 021 620 + z

Table 7. Energy Levels Isoelectronic with N I (in inverse centimeters)

Level	Cu XXIII	Zn XXIV	Ga XXV	Ge XXVI
$2s^22p^3\,{}^4S_{3/2}$	0	0	0	0
${}^2D_{3/2}$	170 940 + x	188 130	208 480 + x	233 620 + x
${}^2D_{5/2}$	230 020 + y	254 110	281 460 + x	313 240 + y
${}^2P_{1/2}$	328 090 + x	357 130	389 300 + x	426 450 + x
${}^2P_{3/2}$	446 810 + z	500 140 + z	560 690 + z	629 140 + z
$2s2p^4\,{}^4P_{5/2}$		956 600	1 016 950	1 079 630
${}^4P_{3/2}$	1 011 200	1 084 810	1 164 010	1 248 770
${}^4P_{1/2}$	1 036 730	1 110 540	1 188 920	
${}^2D_{3/2}$	1 249 750 + x	1 328 550	1 412 600 + x	1 504 300 + x
${}^2D_{5/2}$	1 284 350 + y	1 371 750	1 466 280 + x	1 568 940 + y
${}^2S_{1/2}$	1 426 650 + x	1 516 340	1 612 340 + x	1 716 570 + x
${}^2P_{3/2}$	1 485 730 + y	1 578 630	1 678 870 + x	1 787 390 + y
${}^2P_{1/2}$	1 646 790 + z	1 766 650 + z	1 896 410 + z	2 037 790 + z
$2p^5\,{}^2P_{3/2}$	2 317 810 + y	2 451 700 + z	2 593 060 + x	2 742 910 + y
${}^2P_{1/2}$		2 656 040 + z		

Table 8. Energy Levels Isoelectronic with C I (in inverse centimeters)

Level	Cu XXIV	Zn XXV	Ga XXVI	Ge XXVII
$2s^22p^2\,{}^3P_0$	0	0	0	0
${}^3P_1$	132 110 + x	157 710 + x	186 880 + x	
${}^3P_2$	188 160 + x	218 070 + x	251 610 + x	287 920 + x
$2s2p^3\,{}^3D_1$		1 026 180	1 098 140	
${}^3P_2$	1 196 160 + x	1 295 060 + x	1 401 740 + x	1 516 880 + x
${}^3S_1$	1 336 170 + x	1 428 130 + x	1 527 360 + x	1 633 800 + x
${}^1D_2$		1 514 880 + x		

Table 9. Predicted Wavelengths of Magnetic-Dipole Transitions (in angstroms)[a]

	Cu	Zn	Ga	Ge
$2s^22p^5$				
$^2P_{3/2}$–$^2P_{1/2}$	592.00 H	507.95	437.83	379.55 H
$2s^22p^4$				
$^3P_2$–$^3P_1$		558.47	477.71	410.56 H
$^3P_0$–$^3P_1$		1455.18	1114.21	859.25
$^3P_2$–$^1D_2$		374.36	333.99	
$^3P_1$–$^1D_2$		1135.59	1110.12	1083.19
$^3P_1$–$^1S_0$		300.29	273.10	248.23
$2s^22p^3$				
$^4S_{3/2}$–$^2D_{3/2}$		531.55		
$^4S_{3/2}$–$^2D_{5/2}$		393.53		
$^2D_{3/2}$–$^2D_{5/2}$		1515.61		

[a] H indicates wavelengths identified in PLT tokamak spectra by Hinnov *et al.*[13]

order wavelengths on this plate and also on another plate showing only gallium lines. The wavelength of each line was then averaged over all orders in which it appeared on both plates. The accuracy of most gallium wavelengths is estimated to be 0.005 Å unless there occurs some systematic shift with respect to the standards.

The zinc wavelengths were determined by assuming the wavelength of the F I-like transition to be 86.540 Å and adjusting the grating equation so that the second- and third-order wavelengths matched. The averaged wavelengths were used to plot a correction curve for the first-order wavelengths. Each wavelength was then averaged over all orders where it appeared. The accuracy is about 0.005 relative to 86.540 Å for most lines.

The germanium lines were measured relative to a number of Ge XXII (sodiumlike) transitions.[7] The two transitions $3d\ ^2D_{5/2}$–$4f\ ^2F_{7/2}$ and $3d\ ^2D_{3/2}$–$4f\ ^2F_{5/2}$ were also observed in the copper, zinc, and gallium spectra. Our wavelength measurements for these two sodiumlike transitions in copper, zinc, and gallium agree with the published wavelengths of Kononov[7] to within 0.005 Å.

The wavelengths and relative intensities of the spectral lines from the F I, O I, N I, and C I sequences are listed in Tables 1–4. All the listed wavelengths are from the present work, and those transitions that have been previously identified in Refs. 3 and 9 are designated A and B, respectively. The measured wavelengths for the N I and C I sequences are listed in Tables 3 and 4, and except for four previously identified transitions in Cu XXIII (Ref. 9) and four previously identified transitions in Zn XXIV,[3,9] the transitions in the N I and C I sequences represent new identifications. These transitions were identified using recently calculated wavelengths[10] and by extrapolating from the measured wavelengths of lower-Z ions (Z = 22, 24, 26, 27, 28).[11] The spectral lines from the B I, Be I, and Li I sequences are absent in the data. The plasma temperature was apparently not high enough, or the duration of the plasma was not long enough, to produce these highly charged stages of ionization.

The energy levels of the ions isoelectronic with C I, N I, O I, and F I were derived from the observed wavelengths. In many cases, the total number of observed transitions was insufficient to determine all the levels of the lower configuration $2s^22p^k$. In such cases, we have adopted the values recommended by Edlén[6,12] and have designated the relative uncertainties by $+x$, $+y$, etc. In the case of Zn XXIII and Ga XXIV, a complete set of energy levels was obtained. The present values for the levels of Zn XXIII and the calculated values of Edlén[6] agree to within a standard deviation of 198 cm^{-1}. The calculated energy levels are presented in Tables 5–8.

Listed in Table 9 are the predicted wavelengths, based on the energy levels of Tables 5–8, for a number of magnetic-dipole transitions within the ground configurations of the F I, O I, and N I isoelectronic sequences. The three transitions indicated by H have recently been identified in Princeton Large Torus (PLT) tokamak spectra.[13]

ACKNOWLEDGMENTS

B. Dohne developed the photographic plates, produced photographic enlargements of the spectra, and suggested improvements in the plate-handling procedures and in the vacuum techniques. We thank T. Bristow for coordination of the experiments at the University of Rochester. G. Gregory, W. Watson, and the OMEGA operations staff provided invaluable technical assistance. We thank B. Edlén for reviewing the manuscript and for indicating fundamental improvements.

This research was supported by the U.S. Department of Energy under contract DE-AI08-84-DP40092/26. The research and materials incorporated in this work were partially developed at the National Laser Users Facility at the University of Rochester's Laboratory for Laser Energetics, with financial support from the U.S. Department of Energy under contract DE-AC08-80DP40124. Some of the targets used in this research were supplied by KMS Fusion, Inc., and by the University of Rochester Laser Fusion Feasibility Project.

REFERENCES

1. S. O. Kastner, W. M. Neupert, and M. Swartz, "Solar-flare emission lines in the range from 66 to 171 Å; $2s^r2p^k$–$2s^{r-1}2p^{k+1}$ transitions in highly ionized iron," Astrophys. J. **191**, 261 (1974).
2. B. C. Stratton, W. L. Hodge, H. W. Moos, J. L. Schwob, S. Suckewer, M. Finkenthal, and S. Cohen, "Spectra of germanium and selenium in the 50–350-Å region from the PLT tokamak plasma," J. Opt. Soc. Am. **73**, 877 (1983).
3. W. E. Behring, L. Cohen, G. A. Doschek, and U. Feldman, "Transitions of Zn XXII, Zn XXIII, Zn XXIV, Ge XXIV, and Ge XXV observed in laser-produced plasmas," J. Opt. Soc. Am. **66**, 376 (1976).
4. J. M. Soures, R. J. Hutchison, S. D. Jacobs, L. D. Lund, R. L. McCrory, and M. C. Richardson, "OMEGA–a short wavelength laser for fusion experiments," presented at the Tenth Annual Meeting of the American Nuclear Society, Philadelphia, Pa., 1983.
5. J. Bunkenberg, J. Bolas, D. C. Brown, J. Eastman, J. Hoose, R. Hopkins, L. Iwan, S. D. Jacobs, J. H. Kelly, S. Kumpan, S. Letzring, D. Lonobile, L. D. Lund, G. Mouron, S. Refermak, W. Seka, J. M. Soures, and K. Walsh, "The OMEGA high power phosphate glass system: design and performance," IEEE J. Quantum Electron. **QE-17**, 1620 (1981).
6. B. Edlén, "Comparison of theoretical and experimental level values of the $n = 2$ complex in ions isoelectronic with Li, Be, O, and F," Phys. Scr. **28**, 51 (1983).
7. E. Ya. Kononov, A. N. Ryabtsev, and S. S. Churilov, "Spectra of sodium-like ions Cu XIX–Br XXV," Phys. Scr. **19**, 328 (1979).
8. W. E. Behring, R. J. Ugiansky, and U. Feldman, "High resolution rocket EUV solar spectrograph," Appl. Opt. **12**, 528 (1973).
9. E. Ya. Kononov, V. I. Kovalev, A. N. Ryabtsev, and S. S. Churilov,

"Laser–plasma spectra of ions of elements from Fe to Br with 15–24 lost electrons, recorded in the 50–150 Å range," Sov. J. Quantum Electron. 7, 111 (1977).

10. K. T. Cheng, Y.-K. Kim, and J. P. Desclaux, "Electric dipole, quadrupole, and magnetic dipole transition probabilities of ions isoelectronic to the first-row atoms, Li through F," At. Data Nucl. Data Tables **24**, 111 (1979).
11. K. D. Lawson, N. J. Peacock, and M. F. Stamp, "Allowed and forbidden $n = 2 - 2$ transitions of the elements Ti, Cr, Fe, Co, and Ni in tokamak discharges," J. Phys. B 14, 1929 (1981).
12. B. Edlén, "Accurate values of the energy intervals in the configurations $1s^2\,2s^22p^k$ (k = 1–5)," Phys. Scr. **26**, 71 (1982).
13. E. Hinnov, S. Suckewer, S. Cohen, and K. Sato, "Observed transitions in n = 2 ground-state configurations of copper, nickel, iron, chromium, and germanium in tokamak discharges," Phys. Rev. A **25**, 2293 (1982).