Spectra and energy levels of Cu XXII, Cu XXIII, Cu XXIV, and Cu XXV

J. O. Ekberg, J. F. Seely, C. M. Brown, and U. Feldman

E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, D.C. 20375-5000

M. C. Richardson

Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623-1299

W. E. Behring

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

Received October 20, 1986; accepted November 25, 1986

Transitions in highly ionized copper in the wavelength range 65–121 Å have been identified in spectra recorded at the University of Rochester's 24-beam Omega laser facility. Wavelengths and energy levels are presented for oxygenlike Cu XXII, nitrogenlike Cu XXIII, carbonlike Cu XXIV, and boronlike Cu XXV. The wavelengths of magnetic dipole transitions within the ground configurations are predicted from the energy levels.

INTRODUCTION

Transitions of the type $2s$–$2p$ in highly ionized copper were identified by Kononov *et al.*[1] and by Behring *et al.*[2] in spectra from laser-produced plasmas. The spectra reported in Ref. 2 were produced at the University of Rochester's Omega laser facility. Small targets were spherically irradiated by six beams of the frequency-tripled (λ = 351 nm) Omega laser, and the focused laser intensity was 1×10^{14} W/cm^2. Transitions in F-like, O-like, N-like, and C-like copper were identified. In the present work, copper-coated plastic spheres were irradiated by 24 Omega beams, and the focused laser intensity was 6×10^{15} W/cm^2. The plasmas were much hotter and brighter than the plasmas produced by six beams, and a number of new identifications in O-like through B-like copper have been made.

EXPERIMENT

The targets were plastic spheres 600 μm in diameter and coated with 1 μm of copper. Each of the 24 Omega beams was focused onto the surface of the target, and the diameter of each focal spot was 50 μm. The energy in each laser beam was 50 J, the pulse duration was 450 psec, and the focused intensity was 6×10^{15} W/cm^2.[2,3,4] The 24 focal spots were arranged in a spherically symmetric pattern.

Spectra were recorded by a 3-m grazing-incidence spectrograph.[5] The spectrograph was fitted with a gold-coated grating with 1200 lines/mm, and the angle of incidence was 88°. The grating was blazed at an angle of 4° 7′, and spectral lines were observed from 20 to 300 Å. Radiation from the target was focused onto the entrance slit of the spectrograph by a gold-coated cylindrical mirror that was positioned 130 cm from the target and 70 cm in front of the entrance slit. The line image formed by the mirror was crossed at an angle of 1° with the entrance slit, and this provided spatial resolution of the target in one dimension. This imaging system is described in detail in Ref. 6. The spectra were recorded on Kodak-type SWR photographic plates, and the radiation from five laser shots was integrated into each exposure.

RESULTS

The wavelengths were measured using several previously measured[7–9] Na-like, F-like, and O-like copper transitions as standards. Many of the transitions were observed in second and third orders. The wavelengths were measured to an accuracy of ±0.015 Å, and the wavelength separation between two closely spaced lines could be measured to an accuracy of ±0.005 Å. The measured wavelengths and the classification of the spectral lines in O-like through B-like copper are listed in Table 1. All the previously observed[1,2] transitions in F-like through C-like copper were identified, and a number of new identifications were made for O-like through B-like copper. These new identifications were made on the basis of Edlén's recommended wavelengths.[10–13] Transitions in Li-like and Be-like copper were also identified, and these observations were discussed by Brown *et al.*[14]

The energy levels for Cu XXII and Cu XXIII were derived from the measured wavelengths and are presented in Table

0740-3224/87/030420-04$02.00

Table 1. Wavelengths (in Ångstroms) and Classifications of Spectral Lines in Cu XXII, Cu XXIII, Cu XXIV, and Cu XXV

Ion	Transition		Int.[a]	Observed			Predicted[d]
				Present	Previous[b]	Previous[c]	
Cu XXII							
	$2s^22p^4\ {}^3P_2$–$2s2p^5$	${}^1P_1$	2[e]	65.417		65.43	65.434
	${}^1D_2$	${}^1P_1$	30	77.512	77.521	77.51	77.517
	${}^3P_2$	${}^3P_1$	15	83.183	83.170	83.18	83.171
	${}^3P_1$	${}^3P_0$	5	88.395		88.39	88.385
	${}^3P_2$	${}^3P_2$	25	90.276	90.257	90.27	90.256
	${}^3P_0$	${}^3P_1$	5	90.864		90.85	90.853
	${}^1S_0$	${}^1P_1$	4	93.302		93.31	93.296
	${}^3P_1$	${}^3P_1$	5	95.222		95.21	95.211
	${}^3P_1$	${}^3P_2$	5	104.620		104.61	104.611
	${}^1D_2$	${}^3P_2$	3	114.974			114.975
	$2s2p^5\ {}^3P_1$–$2p^6$	${}^1S_0$	1	74.383			74.379
	${}^1P_1$	${}^1S_0$	10	98.180			98.179
Cu XXIII							
	$2s^22p^3\ {}^2D_{3/2}$–$2s2p^4$	${}^2P_{1/2}$	2	67.759			67.752
	${}^4S_{3/2}$	${}^2S_{1/2}$	1	70.073			70.077
	${}^2D_{3/2}$	${}^2P_{3/2}$	1	76.076			76.072
	${}^2D_{3/2}$	${}^2S_{1/2}$	5	79.615			79.608
	${}^2D_{5/2}$	${}^2P_{3/2}$	20	79.664	79.636	79.65	79.657
	${}^4S_{3/2}$	${}^2D_{3/2}$	1	80.057			80.042
	${}^2P_{3/2}$	${}^2P_{1/2}$	15[f]	83.340	83.335	83.35	83.352
	${}^2P_{1/2}$	${}^2S_{1/2}$	5	91.000	91.028		90.984
	${}^2D_{3/2}$	${}^2D_{3/2}$	5	92.728	92.695	92.72	92.723
	${}^2D_{5/2}$	${}^2D_{5/2}$	10[f,g]	94.888	94.847	94.83	94.855
	${}^4S_{3/2}$	${}^4P_{1/2}$	70[h]	96.485	96.457		96.427
	${}^4S_{3/2}$	${}^4P_{3/2}$	4[i]	98.848	98.892		98.879
	${}^2P_{1/2}$	${}^2D_{3/2}$	1	108.519			108.528
	${}^4S_{3/2}$	${}^4P_{5/2}$	4[i]	111.071			111.057
	$2s2p^4\ {}^2D_{3/2}$–$2p^5$	${}^2P_{1/2}$	1	80.400			80.372
	${}^2D_{3/2}$	${}^2P_{3/2}$	2	93.667			93.613
	${}^2D_{5/2}$	${}^2P_{3/2}$	5[f]	96.845	96.762		96.778
	${}^2P_{3/2}$	${}^2P_{1/2}$	4[f,g]	99.243			99.191
Cu XXIV							
	$2s^22p^2\ {}^3P_2$–$2s2p^3$	${}^1D_2$	4	82.195			82.209
	${}^3P_1$	${}^3S_1$	1	83.084	83.052		83.056
	${}^1D_2$	${}^1P_1$	15[j]	83.340			83.301
	${}^3P_2$	${}^3S_1$	7	87.128	87.107		87.130
	${}^1S_0$	${}^1P_1$	10[j,g]	94.888			94.892
	${}^3P_1$	${}^3P_1$	5[j]	96.845			96.818
	${}^1D_2$	${}^1D_2$	8	96.930			96.979
	${}^3P_1$	${}^3P_0$	1	98.444			98.404
	${}^3P_2$	${}^3P_2$	4[j,g]	99.243	99.206		99.210
	${}^3P_0$	${}^3D_1$	3	104.292			104.340
	${}^3P_1$	${}^3D_2$	3	119.572			119.580
	${}^3P_2$	${}^3D_3$	2	120.442			120.394
	$2s2p^3\ {}^3D_2$–$2p^4$	${}^3P_1$	4	85.226			85.192
	${}^3D_1$	${}^3P_0$	2	87.055			87.021
	${}^3D_1$	${}^3P_2$	3	97.639			97.596
	${}^3D_2$	${}^3P_2$	1	98.576			98.554
	${}^3P_0$	${}^3P_1$	3	100.637			100.618
	${}^3D_3$	${}^3P_2$	7	103.702			103.730
	${}^3P_2$	${}^3P_1$	4	105.760			105.727
	${}^1P_1$	${}^1S_0$	2	105.859			105.821
Cu XXV							
	$2s2p^2\ {}^4P_{1/2}$–$2p^3$	${}^4S_{3/2}$	2	97.272			97.278
	${}^4P_{3/2}$	${}^4S_{3/2}$	3	107.659			107.661
	${}^4P_{5/2}$	${}^4S_{3/2}$	3	117.507			117.510

[a] Intensity based on visual estimate of plate darkening.
[b] Behring *et al.*[2]
[c] Kononov *et al.*[1]
[d] Predicted by Edlén.[10–13]
[e] Blend with cold line from lower ionization stage.
[f] Blend with Cu XXIV.
[g] Blend with second-order line.
[h] Possibly blended with Cu XXV.
[i] Blend with Cu XXVII.
[j] Blend with Cu XXIII.

Table 2. Energy Levels (in 10^3 cm^{-3}) for Cu XXII and Cu XXIII

Ion	Level	Present	Predicted[a]
Cu XXII	$2s^22p^4\ ^3P_2$	0	0
	$^3P_0$	101.62	101.66
	$^3P_1$	151.99	152.04
	$^1D_2$	237.95	238.20
	$^1S_0$	456.29	456.39
	$2s2p^5\ ^3P_2$	1107.71	1107.96
	$^3P_1$	1202.17	1202.34
	$^3P_0$	1283.28	1283.45
	$^1P_1$	1528.08	1528.25
	$2p^6\ ^1S_0$	2546.61	2546.79
Cu XXIII	$2s^2p^3\ ^4S_{3/2}$	0	0
	$^2D_{3/2}$	170.86	170.85
	$^2D_{5/2}$	230.07	230.03
	$^2P_{1/2}$	327.90	327.91
	$^2P_{3/2}$	446.78	447.10
	$2s2p^4\ ^4P_{5/2}$	900.33	900.44
	$^4P_{3/2}$	1011.65	1011.34
	$^4P_{1/2}$	1036.43	1037.05
	$^2D_{3/2}$	1249.11	1249.34
	$^2D_{5/2}$	1283.94	1284.27
	$^2S_{1/2}$	1427.08	1427.01
	$^2P_{3/2}$	1485.34	1485.40
	$^2P_{1/2}$	1646.68	1646.83
	$2p^5\ ^2P_{3/2}$	2316.72	2317.56
	$^2P_{1/2}$	2492.89	2493.56

[a] Predicted by Edlén.[10,11]

2. The overall accuracy of these energy levels is ±200 cm^{-1}. From these energy levels, we have calculated the wavelengths of the magnetic dipole transitions between levels within the $2s^22p^4$ and $2s^22p^3$ ground configurations of the O-like and N-like copper ions. The present predicted wavelengths, the previous predictions of Kaufman and Sugar,[15] and the measurements of Hinnov *et al.*[16] are listed in Table 3. The observed Cu XXIV transitions were insufficient to enable the energy levels to be determined accurately.

ACKNOWLEDGMENTS

The experiments were coordinated by F. J. Marshall. W. Watson, G. Pien, and the Omega Laser Operations Staff provided expert technical assistance. This work 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.

J. O. Ekberg is also with Sachs/Freeman Associates, Landover, Maryland 20785; permanent address, Department of Physics, University of Lund, Lund, Sweden.

REFERENCES

1. 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).
2. W. E. Behring, J. F. Seely, S. Goldsmith, L. Cohen, M. C. Richardson, and U. Feldman, "Transitions of the type 2s–2p in highly ionized Cu, Zn, Ga, and Ge," J. Opt. Soc. Am. B 2, 886 (1985).
3. 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," in *Proceedings of the Tenth Symposium on Fusion Engineering* (Institute of Electrical and Electronics Engineers, New York, 1984), p. 1392.
4. M. C. Richardson, P. W. McKenty, F. J. Marshall, C. P. Verdon, J. M. Soures, R. L. McCrory, O. Barnouin, R. S. Craxton, J. Delettréz, R. L. Hutchison, P. A. Jaanimagi, R. Keck, T. Kessler, H. Kim, S. A. Letzring, D. M. Roback, W. Seka, S. Skupsky, B. Yaakobi, S. M. Lane, and S. Prussin, "Ablatively driven targets imploded with the 24 UV beam Omega system," in *Proceedings of the 7th Meeting on Laser Interaction and Related Plasma Phenomena*, H. Hora, ed. (Plenum, New York, 1986), Vol. 7.
5. W. E. Behring, R. J. Ugiansky, and U. Feldman, "High resolution rocket EUV solar spectrograph," Appl. Opt. 12, 528 (1973).
6. W. E. Behring, C. M. Brown, U. Feldman, J. F. Seely, J. H.

Table 3. Predicted and Observed Wavelengths (in Ångstroms) for Magnetic Dipole Transitions in Cu XXII and Cu XXIII

Ion	Transition	Predicted: Present	Predicted: Previous[a]	Observed[b]
Cu XXII	$2s^22p^4\ ^3P_1–^1S_0$	328.63 ± 0.1	328.6 ± 0.3	
	$^3P_2–^1D_2$	420.25 ± 0.2	419.8 ± 0.5	420.0 ± 0.3
	$^1D_2–^1S_0$	458.01 ± 0.2	458.3 ± 0.6	
	$^3P_2–^3P_1$	657.93 ± 0.4	657.7 ± 1.2	657.7 ± 0.3
	$^3P_1–^1D_2$	1163.3 ± 1	1161 ± 4	
	$^3P_1–^3P_0$	1985.4 ± 4	1985 ± 11	
Cu XXIII	$2s^22p^3\ ^4S_{3/2}–^2P_{3/2}$	223.83 ± 0.1	223.66 ± 0.14	
	$^4S_{3/2}–^2P_{1/2}$	304.97 ± 0.1	304.96 ± 0.26	
	$^2D_{3/2}–^2P_{3/2}$	362.43 ± 0.1	362.0 ± 0.4	
	$^4S_{3/2}–^2D_{5/2}$	434.66 ± 0.2	434.7 ± 0.5	434.8 ± 0.3
	$^2D_{5/2}–^2P_{3/2}$	461.44 ± 0.2	460.7 ± 0.6	
	$^4S_{3/2}–^2D_{3/2}$	585.26 ± 0.3	585.3 ± 1.0	585.0 ± 0.3
	$^2D_{3/2}–^2P_{1/2}$	636.80 ± 0.4	636.7 ± 1.2	
	$^2P_{1/2}–^2P_{3/2}$	841.18 ± 0.7	839.0 ± 2.0	
	$^2D_{3/2}–^2D_{5/2}$	1689.1 ± 3	1690 ± 8	1691.0 ± 0.3

[a] Kaufman and Sugar.[15]
[b] Hinnov *et al.*[16]

Underwood, M. C. Richardson, and F. J. Marshall, "Grazing incidence technique to obtain spatially resolved spectra from laser heated plasmas," Appl. Opt. (to be published).

7. U. Feldman, L. Katz, W. E. Behring, and L. Cohen, "Spectra of Fe, Co, Ni, and Cu isoelectronic with Na I and Mg I," J. Opt. Soc. Am. **61**, 91 (1971).
8. E. Ya. Kononov, A. N. Ryabtsev, and S. S. Churilov, "Spectra of sodium-like ions Cu XIX–Br XXV," Phys. Scr. **19**, 328 (1979).
9. J. Sugar and V. Kaufman, "Copper spectra in a laser-generated plasma: measurements and classifications of Cu XII to Cu XXI," J. Opt. Soc. Am. B **3**, 704 (1986).
10. 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).
11. B. Edlén, "Comparison of theoretical and experimental level values of the $n = 2$ configurations in the nitrogen isoelectronic sequence," Phys. Scr. **30**, 135 (1984).
12. B. Edlén, "Comparison of theoretical and experimental level values of the $n = 2$ configurations in the carbon isoelectronic sequence," Phys. Scr. **31**, 345 (1985).
13. B. Edlén, "Comparison of theoretical and experimental level values of the $n = 2$ configurations in the boron isoelectronic sequence," Phys. Scr. **28**, 483 (1983).
14. C. M. Brown, J. O. Ekberg, U. Feldman, J. F. Seely, M. C. Richardson, F. J. Marshall, and W. E. Behring, "Transitions in lithiumlike Cu^{26+} and berylliumklike Cu^{25+} of interest for x-ray laser research," J. Opt. Soc. Am. B (to be published).
15. V. Kaufman and J. Sugar, "Forbidden lines in ns^2np^k ground configurations and *nsnp* excited configurations of Be through Mo atoms and ions," J. Chem. Ref. Data **15**, 321 (1986).
16. E. Hinnov, S. Suckewer, S. Cohen, and K. Sato, "Observed transitions in $n = 2$ ground configurations of copper, nickel, iron, and chromium and germanium in tokamak discharges," Phys. Rev. A **25**, 2293 (1982).