Spectra and energy levels of Sm XXXIV, Eu XXXV, Gd XXXVI, and Yb XXXXII

G. A. Doschek, U. Feldman, C. M. Brown, J. F. Seely, and J. O. Ekberg*

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

W. E. Behring

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

M. C. Richardson

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

Received May 6, 1987; accepted October 5, 1987

We present wavelengths and energy levels based on extreme-ultraviolet and x-ray transitions in the ions Sm^{+33}, Eu^{+34}, Gd^{+35}, and Yb^{+41} of the Cu I isoelectronic sequence. The sources of the spectra were laser-produced plasmas generated by the OMEGA laser facility at the University of Rochester's Laboratory for Laser Energetics. The photographic spectra were recorded by a 3-m grazing-incidence spectrograph. The spectral lines fall between about 10 and 115 Å, and we compare our results with previous measurements where available.

INTRODUCTION

In this paper we classify and present wavelengths for transitions in the ions Sm^{+33}, Eu^{+34}, Gd^{+35}, and Yb^{+41} of the Cu I isoelectronic sequence. The transitions are of the type nl–$n'l'$, where $n = 4, 5$; $n' = 4, 5, 6$; $l = 0 \rightarrow 4$, and $l' = 0 \rightarrow 5$. We also present energy levels derived from the wavelengths. Our spectra were obtained using the OMEGA laser facility at the University of Rochester's Laboratory for Laser Energetics. The targets were irradiated by frequency-tripled (3510-Å) Nd:glass laser beams.

Previous work on transitions in highly ionized Cu I sequence ions is discussed by Reader and Luther[1] and by Seely *et al.*[2] Reader and Luther[1] present wavelengths and energy levels for Sm^{+33}, Gd^{+35}, and Yb^{+41}. Some of our wavelengths differ from their wavelengths by as much as 0.1 Å. Transitions in the Cu I sequence are of interest because of the possibility of obtaining population inversions by recombination between levels such as 5d and nf, which could be useful in x-ray laser research.

EXPERIMENT

The spectra were recorded using a 3-m grazing-incidence spectrograph originally developed for solar rocket observations.[3] A 1200-line/mm gold-coated Bausch & Lomb replica grating was used. The angle of incidence is 88°, and the blaze angle is 2° 35′. The blaze angle corresponds to a wavelength of about 60 Å.

The spectrograph is enclosed in a vacuum chamber along with a gold-coated cylindrical beryllium mirror that is used to focus light onto the 10-μm entrance slit of the spectrograph.[4] The mirror is 130 cm from the target and 70 cm in front of the entrance slit. The function of the mirror is mainly to provide sufficient intensity, but, because it forms a line image of the source that is adjusted to cross the entrance slit at an angle of 1°, some spatial resolution along the length of the slit is also obtained. Spectra are recorded on Kodak 101-05 plates. Four different masks can be rotated into the light path between the grating and the entrance slit. This provides a method for discriminating between spectral lines of different targets on the same photographic plate, i.e., different exposures produce separate tracks. The targets are described below.

Samarium

Two slab chunks of samarium were used, with diameters of 645 and 680 μm. The chunks were illuminated by 20 of the 24 available laser beams. The beams were focused at a distance of eight target radii beyond the center of the targets in order to provide reasonably uniform illumination. The first shot delivered a total of 1280 J of energy onto one of the chunks with a pulse-duration time of 540 psec. The second shot delivered 1320 J onto the target in 460 psec.

Europium

The europium target was a glass stalk, 850 μm in diameter, dipped in molten Eu_2O_3. Twenty off-focus laser beams were used, and two shots were recorded on a single photographic plate. The shots delivered about 1400 J of energy onto the target with pulse durations of 430 and 550 psec, respectively.

Gadolinium

The gadolinium targets were glass stalks dipped in molten gadolinium. All 24 beams were used to illuminate the targets in the off-focus mode. Two shots were recorded on a single photographic plate. The shots delivered 940 and 1220 J of energy onto the targets with pulse durations of 410 psec.

0740-3224/88/020243-04$02.00

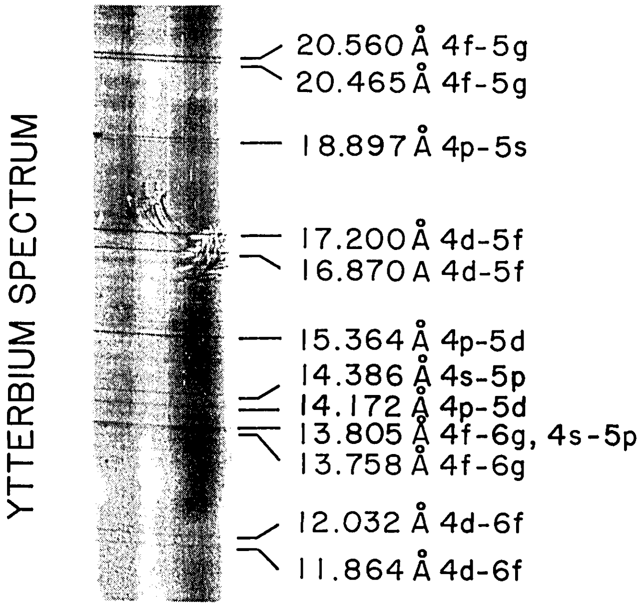

Fig. 1. A portion of the Yb XXXXII spectrum obtained with a 3-m spectrograph at the Laboratory for Laser Energetics.

Ytterbium

The two ytterbium targets were glass stalks 864 μm in diameter dipped in molten ytterbium. The 24 beams were focused onto each of the targets and delivered a total energy of 590 and 690 J, respectively, in about 600 psec. Each shot was recorded on a different photographic plate.

Reference wavelengths were provided by lines of silicon, oxygen, and carbon, produced using glass-microballoon and CH targets.

RESULTS

Spectral lines were observed between about 10 and 115 Å. The plates were measured with a Grant microdensitometer. Using the wavelength standards, the absolute accuracy of measured wavelengths is determined to be ±0.015 Å. Relative wavelength accuracy is ±0.005 Å. Classifications of spectral lines were made using previously published classifications by Reader and Luther[1] and calculated wavelengths from a multiconfiguration Dirac–Fock computer program written by Grant and collaborators.[5,6] The calculations include quantum-electrodynamic and Breit corrections. The calculations were done using the extended average level option and include all the Cu-like levels with principal quantum numbers $n = 4, 5, 6$. The calculated wavelengths usually agree with the experimental wavelengths to within a few hundredths of an angstrom. A portion of the ytterbium spectrum is shown in Fig. 1.

The classifications, wavelengths, and intensity estimates of the lines that we have observed are given in Table 1 along with the predicted wavelengths and the previously observed wavelengths of Reader and Luther.[1] The intensity scale for each ion is different and arbitrary. Intensities are visual estimates based on photographic plate darkening. For Sm^{+33} the differences between our wavelengths and the Reader–Luther[1] wavelengths are small and generally less than 0.05 Å. The Reader–Luther[1] wavelengths are systematically larger than our wavelengths. We have observed two Sm^{+33} transitions (4*f*–6*g*) that are not given by Reader and Luther.[1] Reader and Luther[1] did not record europium spectra. For Gd^{+35}, the differences between the present and the Reader–Luther[1] wavelengths are again less than about 0.05 Å, with the latter wavelengths being larger. We have ob-

Table 1. Wavelengths (Å) and Classifications of Spectral Lines in Sm XXXIV and Eu XXXV[a]

	Samarium				Europium		
Transition	Int.	Pres.	Prev.	Pred.	Int.	Pres.	Pred.
$4s\ {}^2S_{1/2}-4p\ {}^2P_{3/2}$	1	113.504	113.509	113.356	10	107.829	107.674
$4s\ {}^2S_{1/2}-5p\ {}^2P_{1/2}$	7	20.759 bl	20.815 bl	20.789	8	19.779 bl	19.784
$4s\ {}^2S_{1/2}-5p\ {}^2P_{3/2}$	2	20.158	20.214	20.178	8	19.164	19.180
$4p\ {}^2P_{1/2}-4d\ {}^2D_{3/2}$	4	82.155	82.206	82.173	25	78.609	78.637
$4p\ {}^2P_{3/2}-4d\ {}^2D_{3/2}$	—	—	111.169	111.007	—	—	107.890
$4p\ {}^2P_{3/2}-4d\ {}^2D_{5/2}$	2	103.551	103.571	103.482	—	100.208	100.139
$4p\ {}^2P_{1/2}-5s\ {}^2S_{1/2}$	3	25.126	25.164	25.165	4	23.806	23.859
$4p\ {}^2P_{3/2}-5s\ {}^2S_{1/2}$	3	27.283	27.321	27.339	10	25.948	25.997
$4p\ {}^2P_{1/2}-5d\ {}^2D_{3/2}$	7	20.759 bl	20.815 bl	20.780	5	19.721 bl	19.742
$4p\ {}^2P_{3/2}-5d\ {}^2D_{5/2}$	7	22.054	22.109	22.087	15	21.008	21.031
$4d\ {}^2D_{3/2}-4f\ {}^2F_{5/2}$	1	96.983	97.010	97.064	15	93.840	93.933
$4d\ {}^2D_{5/2}-4f\ {}^2F_{5/2}$	—	—	—	103.655	0	100.697	100.720
$4d\ {}^2D_{5/2}-4f\ {}^2F_{7/2}$	2	102.223	102.249	102.304	12	99.209	99.282
$4d\ {}^2D_{3/2}-5p\ {}^2P_{1/2}$	—	—	—	33.034	2	31.192	31.260
$4d\ {}^2D_{5/2}-5p\ {}^2P_{3/2}$	—	—	—	32.183	2	30.361	30.428
$4d\ {}^2D_{3/2}-5f\ {}^2F_{5/2}$	9	24.634	24.680	24.689	20	23.401	23.450
$4d\ {}^2D_{5/2}-5f\ {}^2F_{7/2}$	10	24.992	25.038	25.046	18	23.755	23.801
$4d\ {}^2D_{3/2}-6f\ {}^2F_{5/2}$	0	17.553	17.587	17.575	4	16.641	16.664
$4d\ {}^2D_{5/2}-6f\ {}^2F_{7/2}$	3	17.732	17.788	17.765	6	16.830	16.850
$4f\ {}^2F_{5/2}-5d\ {}^2D_{3/2}$	—	—	—	38.985	—	—	36.642
$4f\ {}^2F_{7/2}-5d\ {}^2D_{5/2}$	—	—	—	38.705	1	36.303	36.376
$4f\ {}^2F_{5/2}-5g\ {}^2G_{7/2}$	9	30.975	30.998	31.060	25	29.259	29.337
$4f\ {}^2F_{7/2}-5g\ {}^2G_{9/2}$	15	31.070	31.096	31.155	25	29.356	29.432
$4f\ {}^2F_{5/2}-6g\ {}^2G_{7/2}$	2	20.902	—	20.948	5	19.721 bl	19.779
$4f\ {}^2F_{7/2}-6g\ {}^2G_{9/2}$	2	20.948	—	20.996	8	19.779 bl	19.828
$5g\ {}^2G_{7/2}-6h\ {}^2H_{9/2}$	3	63.565	63.552	63.666	7	59.912	60.068
$5g\ {}^2G_{9/2}-6h\ {}^2H_{11/2}$			63.619	63.739	7	59.987	60.141

Table 1. Continued

	Gadolinium				Ytterbium			
Transition	Int.	Pres.	Prev.	Pred.	Int.	Pres.	Prev.	Pred.
$4s\,^2S_{1/2}$–$4p\,^2P_{3/2}$	20	102.459	102.497	102.309	5	75.816 bl	75.914 bl	75.702
$4s\,^2S_{1/2}$–$5p\,^2P_{1/2}$	3	18.839	18.847	18.848	3	14.386	14.41	14.388
$4s\,^2S_{1/2}$–$5p\,^2P_{3/2}$	7	18.239	18.251	18.251	5	13.805 bl	13.80	13.824
$4p\,^2P_{1/2}$–$4d\,^2D_{3/2}$	10	75.259	75.316	75.277	5	58.190	58.265	58.217
$4p\,^2P_{3/2}$–$4d\,^2D_{3/2}$	5	105.098	105.132	104.938	—	—	90.270	90.041
$4p\,^2P_{3/2}$–$4d\,^2D_{5/2}$	20	97.026	97.074	96.962	4	80.741	80.824	80.704
$4p\,^2P_{1/2}$–$5s\,^2S_{1/2}$	10	22.610 bl	22.646 b1	22.650	1	16.958	—	16.975
$4p\,^2P_{3/2}$–$5s\,^2S_{1/2}$	7	24.717	24.756	24.755	3	18.897	—	18.925
$4p\,^2P_{1/2}$–$5d\,^2D_{3/2}$	3	18.756	18.757	18.777	4	14.172	—	14.190
$4p\,^2P_{3/2}$–$5d\,^2D_{5/2}$	10	20.030	20.055	20.049	9	15.364	—	15.380
$4p\,^2P_{1/2}$–$6d\,^2D_{3/2}$	—	—	—	—	1	10.18	—	10.130
$4p\,^2P_{3/2}$–$6d\,^2D_{5/2}$	1	14.203	—	14.232	0	10.81	—	10.753
$4d\,^2D_{3/2}$–$4f\,^2F_{5/2}$	10	90.875	90.933	90.966	5	75.816 bl	75.914 bl	75.946
$4d\,^2D_{5/2}$–$4f\,^2F_{5/2}$	—	—	—	97.951	—	—	—	84.159
$4d\,^2D_{5/2}$–$4f\,^2F_{7/2}$	15	96.349	96.398	96.426	2	81.991	82.077	82.074
$4d\,^2D_{3/2}$–$5p\,^2P_{1/2}$	1	29.562	—	29.628	—	—	—	22.130
$4d\,^2D_{5/2}$–$5p\,^2P_{3/2}$	1	28.765	—	28.815	1	21.347	—	21.395
$4d\,^2D_{3/2}$–$5f\,^2F_{5/2}$	10	22.262	22.295	22.301	4	16.870	16.91	16.901
$4d\,^2D_{5/2}$–$5f\,^2F_{7/2}$	10	22.610 bl	22.646	22.648	8	17.200	17.239	17.223
$4d\,^2D_{3/2}$–$6f\,^2F_{5/2}$	3	15.794	—	15.821	2	11.864	—	11.890
$4d\,^2D_{5/2}$–$6f\,^2F_{7/2}$	5	15.981	—	16.005	3	12.032	—	12.059
$4f\,^2F_{5/2}$–$5d\,^2D_{3/2}$	2	34.448	—	34.506	—	—	—	24.920
$4f\,^2F_{7/2}$–$5d\,^2D_{5/2}$	2	34.196	—	34.254	—	—	—	24.725
$4f\,^2F_{5/2}$–$5g\,^2G_{7/2}$	8	27.695	27.725	27.754	10	20.465	20.55	20.504
$4f\,^2F_{7/2}$–$5g\,^2G_{9/2}$	9	27.794	27.826	27.850	15	20.560	20.65	20.601
$4f\,^2F_{5/2}$–$6g\,^2G_{7/2}$	2	18.671	—	18.706	2	13.758	—	13.792
$4f\,^2F_{7/2}$–$6g\,^2G_{9/2}$	1	18.726	—	18.755	5	13.805 bl	—	13.841
$5g\,^2G_{7/2}$–$6h\,^2H_{9/2}$	3	56.643	56.672	56.766	—	—	—	41.662
$5g\,^2G_{9/2}$–$6h\,^2H_{11/2}$	5	56.722	56.744	56.839	—	—	—	41.736

[a] Int., Visual intensity estimate. The intensity scales for different ions are different. Pres., Wavelengths, this work. Prev., Previous wavelengths from Reader and Luther.[1] Pred., Predicted wavelengths from Grant *et al.*[5]; bl, blend.

served a number of gadolinium lines not reported by Reader and Luther.[1] For Yb^{+41} the differences between our wavelengths and the Reader–Luther[1] wavelengths are sometimes as large as about 0.1 Å. We also observe a number of ytterbium transitions not reported by them. These results are generally consistent with revisions of wavelengths of Zn-like transitions reported by Acquista and Reader.[7] As some of these wavelengths were lowered by amounts as great as 0.07 Å, similar revisions may be implied for the Cu-like ions.

The energy levels relative to the ground states for Sm^{+33}–Yb^{+41} were derived from the measured wavelengths and are given in Table 2. Many of the energy levels depend on the splitting of the $4p$ levels. These were determined experimentally from the two $5s \rightarrow 4p$ transitions. However, because these lines are weak, we believed that the $4p\,^2P_{1/2}$, $4p\,^2P_{3/2}$ splitting could be improved on by using the results of Seely *et al.*[2] These authors found that the difference between the $4p\,^2P_{3/2}$ experimental energy-level value and the theoretical value calculated by the Grant code was the same as the similar difference for the $4p\,^2P_{1/2}$ level for Cu I sequence ions. We therefore calculated this difference for the ions discussed herein for the $4p\,^2P_{3/2}$ level and adopted this difference for the $4p\,^2P_{1/2}$ level. The $4p\,^2P_{1/2}$ energy levels were derived by applying this difference to theoretical $4p\,^2P_{1/2}$ energy levels calculated from the Grant code.

The overall absolute accuracy of the energy levels varies depending on the wavelength. For levels based on lines at 15 Å, the accuracy is ±6700 cm^{-1}. Relative values of these same energy levels are known to within about 2200 cm^{-1}.

Table 2. Observed Energy Levels of Sm XXXIV, Eu XXXV, Gd XXXVI, and Yb XXXXII (in units of 10^3 cm^{-1})

Level	Sm XXXIV	Eu XXXV	Gd XXXVI	Yb XXXXII
$4s\,^2S_{1/2}$	0	0	0	0
$4p\,^2P_{1/2}$	$565.0 + x^a$	$582.6 + x^a$	$600.5 + x^a$	$711.8 + x^a$
$4p\,^2P_{3/2}$	881.0	927.4	976.0	1319.0
$4d\,^2D_{3/2}$	$1782.2 + x$	$1854.7 + x$	$1929.2 + x$	$2430.3 + x$
$4d\,^2D_{5/2}$	1846.7	1925.3	2006.6	2557.5
$4f\,^2F_{5/2}$	$2813.3 + x$	$2920.4 + x$	$3029.7 + x$	$3749.3 + x$
$4f\,^2F_{7/2}$	2825.0	2933.3	3044.5	3777.2
$5s\,^2S_{1/2}$	4546.3	4781.3	5021.8	6610.8
$5p\,^2P_{1/2}$	4817.2	5055.9	5308.1	6951.2
$5p\,^2P_{3/2}$	4960.8	5218.1	5482.8	7243.8
$5d\,^2D_{3/2}$	$5382.2 + x$	$5653.3 + x$	$5932.1 + x$	$7768.0 + x$
$5d\,^2D_{5/2}$	5415.4	5687.5	5968.5	7827.7
$5f\,^2F_{5/2}$	$5841.6 + x$	$6128.0 + x$	$6421.2 + x$	$8358.0 + x$
$5f\,^2F_{7/2}$	5848.0	6135.0	6429.5	8371.5
$5g\,^2G_{7/2}$	$6041.7 + x$	$6338.1 + x$	$6640.4 + x$	$8635.7 + x$
$5g\,^2G_{9/2}$	6043.5	6339.8	6642.4	8641.0
$6d\,^2D_{3/2}$	—	—	—	$10535.0 + x$
$6d\,^2D_{5/2}$	—	—	8016.8	10569.7
$6f\,^2F_{5/2}$	$7479.2 + x$	$7864.0 + x$	$8260.8 + x$	$10859.2 + x$
$6f\,^2F_{7/2}$	7486.3	7867.1	8264.1	10868.7
$6g\,^2G_{7/2}$	$7597.5 + x$	$7991.1 + x$	$8385.6 + x$	$11017.8 + x$
$6g\,^2G_{9/2}$	7598.7	7989.2	8384.7	11020.9
$6h\,^2H_{9/2}$	—	$8007.2 + x$	$8405.9 + x$	—
$6h\,^2H_{11/2}$	—	8006.8	8405.4	—

[a] The energy level of the $4p\,^2P_{1/2}$ level is the calculated one corrected according to the results given by Seely *et al.*[2]

ACKNOWLEDGMENTS

We thank G. D. Ramback and the target fabrication group at Lawrence Livermore National Laboratory for providing the europium, gadolinium, and ytterbium targets. We also thank S. Maxon for his interest and encouragement. We thank the Laser Operations Staff at the Laboratory for Laser Energetics, University of Rochester, for providing excellent technical assistance. The research at the Naval Research Laboratory 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 Laboratory for Laser Energetics, with financial support from the U.S. Department of Energy under contract DE-AC08-80-DP40124.

* Permanent address, Department of Physics, University of Lund, Lund, Sweden.

REFERENCES

1. J. Reader and G. Luther, "The copper isoelectronic sequence," Phys. Scr. **24**, 732 (1982).
2. J. F. Seely, J. O. Ekberg, C. M. Brown, U. Feldman, W. E. Behring, J. Reader, and M. C. Richardson, "Laser-produced spectra and QED effects for Fe-, Co-, Cu-, and Zn-like ions of Au, Pb, Bi, Th, and U," Phys. Rev. Lett. **57**, 2924 (1986).
3. W. E. Behring, R. J. Ugiansky, and U. Feldman, "High-resolution rocket EUV solar spectrograph," Appl. Opt. **12**, 528 (1973).
4. W. E. Behring, J. Underwood, C. M. Brown, U. Feldman, J. F. Seely, F. J. Marshall, and M. C. Richardson, "A grazing-incidence technique to obtain spatially resolved spectra from laser heated plasmas," submitted to Appl. Opt.
5. I. P. Grant, B. J. McKenzie, P. H. Norrington, D. F. Myers, and N. C. Pyper, "An atomic multiconfigurational Dirac–Fock package," Comput. Phys. Commun. **21**, 207 (1980).
6. B. J. McKenzie, I. P. Grant, and P. H. Norrington, "A program to calculate transverse Breit and QED corrections to energy levels in a multiconfiguration Dirac–Fock environment," Comput. Phys. Commun. **21**, 233 (1980).
7. N. Acquista and J. Reader, "$4s^2\ {}^1S_0$–$4s4p\ {}^1P_1$ transitions in zinclike ions," J. Opt. Soc. Am. B **1**, 649 (1984).