Laser-Produced Spectra and QED Effects for Fe-, Co-, Cu-, and Zn-like Ions of Au, Pb, Bi, Th, and U

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Spectra of very highly charged ions of Au, Pb, Bi, Th, and U have been observed in laser-produced plasmas generated by the OMEGA laser. Line identifications in the region 9–110 Å were made for ions in the Fe, Co, Cu, and Zn isoelectronic sequences. Comparison of the measured wavelengths of the Cu-like ions with values calculated with and without QED corrections shows that the inclusion of QED corrections greatly improves the accuracy of the calculated $4s$-$4p$ wavelengths. However, significant differences between the observed and calculated values remain.

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The spectra of very highly charged ions are of great interest for the development of laser fusion[1,2] and for tests of relativistic calculations of the atomic structure of high-Z ions. In this Letter we report spectra observations of highly charged ions of Au, Pb, Bi, Th, and U (Z =79–92) belonging to the FeI, CoI, CuI, and ZnI isoelectronic sequences. Comparison of the measured wavelengths with relativistically calculated theoretical wavelengths shows the importance of QED corrections in the theoretical calculations. This extends to higher Z recent work[3–7] on these sequences for elements up to W (Z=74).

The spectra were generated in laser-produced plasmas at the University of Rochester's Laboratory for Laser Energetics. Solid targets were spherically irradiated by 24 beams of frequency-tripled radiation (wavelength 351 nm) from the OMEGA laser.[8,9] Each beam had an en-

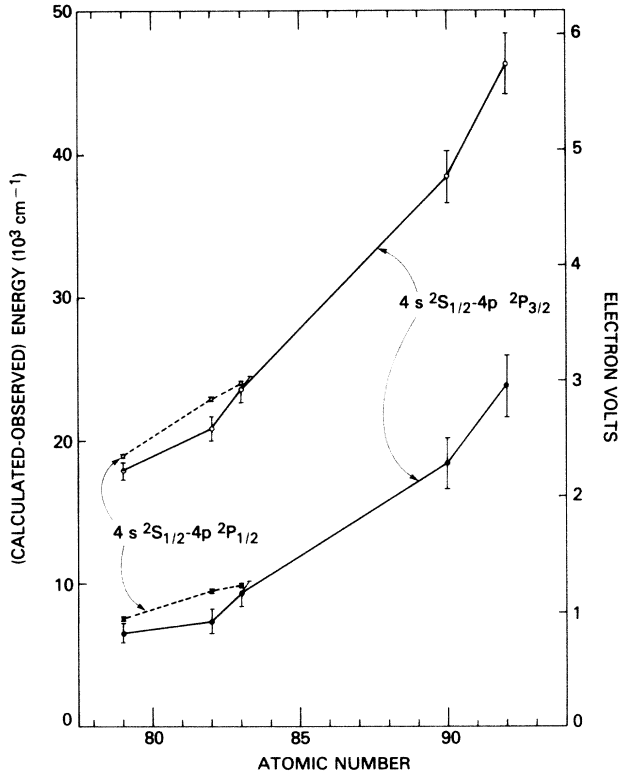

FIG. 1. Comparison of the observed energies of $4s$-$4p$ transitions of Cu-like ions with energies calculated by use of Grant's program without QED corrections (open circles) and with QED corrections (solid circles).

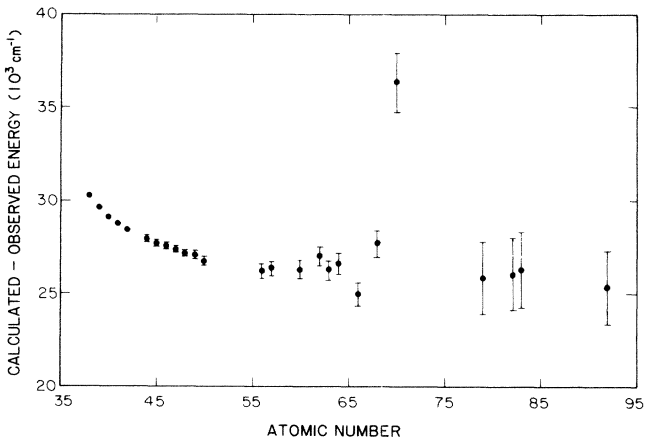

FIG. 2. Comparison of the observed energies of the $3p^63d^9{}^2D_{5/2}$–$3p^53d^{10}{}^2P_{3/2}$ transitions in Co-like ions with energies calculated with Grant's program.

TABLE I. Observed and calculated wavelengths in angstroms for transitions in highly charged ions of Au, Pb, and Bi.

		Au^{49+} - Au^{53+}				Pb^{52+} - Pb^{56+}				Bi^{53+} - Bi^{57+}		
Sequence	Transition	Int.	Obs.	MCDF[a]	MP[b]	Int.	Obs.	MCDF[a]	RHF[c]	Int.	Obs.	MCDF[a]
Fe I	$3p^63d^8\ ^3F_4$ - $3p^53d^9\ (3/2,5/2)_3$	8[d]	24.200	23.996		2	22.420	22.250		6	21.865	21.699
Co I	$3p^63d^9\ ^2D_{5/2}$ - $3p^53d^{10}\ ^2P_{3/2}$	10	24.338	24.186		2	22.557	22.425		8	21.997	21.871
Cu I	$4s\ ^2S_{1/2}$ - $4p\ ^2P_{1/2}$	3	112.485	111.53	112.80	1	104.94	103.90	103.18	1	102.55	101.52
	$4s\ ^2S_{1/2}$ - $4p\ ^2P_{3/2}$	20	48.928	48.771	48.919	3	42.349	42.216	42.093	10	40.394	40.241
	$4p\ ^2P_{1/2}$ - $4d\ ^2D_{3/2}$	16	39.922	39.903	39.928	9	35.181	35.201	35.207	15	33.775	33.759
	$4p\ ^2P_{3/2}$ - $4d\ ^2D_{5/2}$	4	62.653	62.633	62.712	5	57.751	57.769	57.783	8	56.272	56.248
	$4d\ ^2D_{3/2}$ - $4f\ ^2F_{5/2}$	4	59.428	59.483	59.007	1	55.023	55.074	55.081	4	53.624	53.697
	$4d\ ^2D_{5/2}$ - $4f\ ^2F_{7/2}$	2	66.500	66.574	66.063	2	62.361	62.464	62.473	4	61.086	61.183
	$4s\ ^2S_{1/2}$ - $5p\ ^2P_{3/2}$	2	9.539	9.576	9.607							
	$4s\ ^2S_{1/2}$ - $5p\ ^2P_{1/2}$	1	10.075	10.103	10.133							
	$4p\ ^2P_{1/2}$ - $5d\ ^2D_{3/2}$	1	9.764	9.810	9.851							
	$4p\ ^2P_{3/2}$ - $5d\ ^2D_{5/2}$	4	10.887	10.919	10.966	1	9.814	9.852	9.853	7	9.480	9.530
	$4d\ ^2D_{3/2}$ - $5f\ ^2F_{5/2}$	5	11.804	11.840	11.901	4	10.619	10.646	10.646	2	10.253	10.287
	$4d\ ^2D_{5/2}$ - $5f\ ^2F_{7/2}$	5	12.100	12.137	12.210	5	10.889	10.937	10.938	3	10.542	10.576
	$4f\ ^2F_{5/2}$ - $5g\ ^2G_{7/2}$	9	13.984	14.012		3	12.484	12.525	12.527	3	12.055	12.082
	$4f\ ^2F_{7/2}$ - $5g\ ^2G_{9/2}$	10	14.087	14.110		4	12.577	12.623	12.626	3	12.155	12.180
Zn I	$4s^2\ ^1S_0$ - $4s4p\ ^1P_1$	9	48.046	47.865[e]		1	41.689	41.546		8	39.798	39.635

[a]Present calculation using Grant's program, Refs. 11 and 12.
[b]Model potential calculation of Ivanov *et al.*, Ref. 13.
[c]Relativistic Hartree-Fock calculation of Cheng and Kim, Ref. 14.
[d]Blended line.
[e]Calculated wavelengths of Shorer and Dalgarno, Ref. 15, are 47.676 Å (relativistic random-phase approximation) and 47.752 Å (Dirac-Hartree-Fock).

ergy of about 60 J and a duration of about 450 psec. The intensity of the focused laser beams varied from 1×10^{15} to 5×10^{16} W/cm^2. The spectra were photographed in the region 9–112 Å with a 3-m grazing-incidence spectrograph[10] on Kodak 101-05 plates. The spectrograph was fitted with a gold-coated grating ruled with 1200 lines/mm. Light from the target was focused astigmatically onto the entrance slit of the spectrograph by a gold-coated cylindrical mirror. One laser shot was used for each spectrum.

The spectra of the high-Z ions were measured relative to spectra of O^{7+}, Si^{10+}, Si^{11+}, and Si^{12+} originating in the glass stalk and silicone adhesive used to hold the target as well as separate calibration spectra from glass microballoons. The measured wavelengths are given in Tables I and II. The uncertainty of the wavelengths is ±0.015 Å. The intensities are visual estimates of plate darkening. The line identifications were made by isoelectronic extrapolation from lower-Z elements and by comparison with calculated wavelengths.

In Tables I and II the observed wavelengths are compared with various theoretical values. The multiconfiguration Dirac-Fock (MCDF) values with transverse Breit and QED corrections were calculated by us with the computer program of Grant *et al.*[11] and McKenzie, Grant, and Norrington.[12] The QED calculations in this program include second-order vacuum polarization corrections as prescribed by Fullerton and Rinker[17] and self-energy corrections obtained by scaling the hydrogenic $n=1,2$ results of Mohr[18,19] according to $1/n^3$.

For the Cu-like ions the QED corrections have a measurable effect only for the $4s$-$4p$ transitions. In Fig. 1 we compare the observed wavelengths for $4s$-$4p$ transitions in Cu-like ions with wavelengths calculated with the use of Grant's code, both with and without the QED corrections. These calculations were made in the extended average level mode. The energy functional optimized was the statistically weighted average of the energies of the two fine-structure levels at each nl term. The differences are seen to vary systematically. Clearly the inclusion of QED corrections in the calculations improves the accuracy of the results. However, significant differ-

TABLE II. Observed and calculated wavelengths in angstroms for transitions in highly charged ions of Th and U.

		Th^{60+}-Th^{63+}			U^{62+}-U^{65+}		
Sequence	Transition	Int.	Obs.	MCDF[a]	Int.	Obs.	MCDF[a]
Co I	$3p^6 3d^9\,{}^2D_{5/2}$-$3p^5 3d^{10}\,{}^2P_{3/2}$				3	17.561	17.483
Cu I	$4s\,{}^2S_{1/2}$-$4p\,{}^2P_{3/2}$	5	28.990	28.839	2	26.400	26.235
	$4p\,{}^2P_{1/2}$-$4d\,{}^2D_{3/2}$	3	25.180	25.170			
	$4p\,{}^2P_{3/2}$-$4d\,{}^2D_{5/2}$	3	46.830	46.816			
	$4d\,{}^2D_{5/2}$-$4f\,{}^2F_{7/2}$	2	53.154	53.255			
Zn I	$4s^2\,{}^1S_0$-$4s4p\,{}^1P_1$	2	28.703	28.547	1	26.175	26.000[b]

[a]Present calculation by use of the program of Grant *et al.*, Ref. 11, and McKenzie, Grant, and Norrington, Ref. 12.

[b]Calculated values of Shorer, Ref. 16, are 25.847 Å (relativistic random-phase approximation) and 25.876 Å (Dirac-Hartree-Fock).

ences between observed and calculated values still remain.

Figure 2 shows the differences between the observed wavelengths of the $3p^6 3d^9\,{}^2D_{5/2}$-$3p^5 3d^{10}\,{}^2P_{3/2}$ transitions in Co-like ions and those calculated with the Grant code. Except for the transition in Yb^{43+} ($Z=70$), which was considered to be poorly determined,[6] the present measurements are consistent with those of the lower-Z ions.[6]

In conclusion, the agreement between the presently measured transition energies and the transition energies calculated with the Grant code improves with increasing Z except for the Cu-like $4s\,{}^2S_{1/2}$-$4p\,{}^2P_{1/2}$ and $4s\,{}^2S_{1/2}$-$4p\,{}^2P_{3/2}$ transitions and the Zn-like $4s^2\,{}^1S_0$-$4s4p\,{}^1P_1$ transition. For these transitions, the discrepancies grow with Z and indicate a departure from the scaled hydrogenic QED contribution to the $4s$ energy.

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