Systematic Studies of the n=2 to n=3,4 Transitions in the Ions of Elements Cu through As Isoelectronic with Li I through Na I Produced by Laser Irradiation

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1 Introduction

Laser produced plasmas provide rich X-ray spectra. Their identification is of importance for the physics of ICF and X-ray lasers, of laboratory X-ray sources and of hot astrophysical objects. X-ray spectra of 5 elements (Z=29 through 33) have been measured at the LULI laser facility as part of a systematic investigation of the medium-Z elements. The laser pulse conditions were 600 ps duration, frequency-doubled and 8 to 35 J focused on 80 μm focal spots, leading to irradiations of 2×10^{14} to 10^{15} Wcm^{-2}. Spectra were recorded in the ranges 6-8 Å and 7.55-9.55 Å by means of two flat crystal spectrographs (respectively PET and ADP crystals). The size of the plasma limits the linewidths to about 0.004 Å. The laser beam was focused at normal incidence onto the target surface. The spectra were recorded on films with an observation direction perpendicular to the laser axis and to the main plasma expansion.

Magnesium has been used as a tracer element for wavelength calibration, some targets being a mixture of Mg and the element being investigated. Only the Ly_α doublet (λ8.4194/8.4253 Å) and Mg XI He_α (λ9.1682 Å) were obtained, and they were supplemented by theoretical wavelengths of well-resolved lithium-like lines at the short wavelength end of our observations. The wavelength uncertainty is 0.003 Å for well-resolved lines but most of the emission peaks are blends of several transitions whose relative intensities depend on plasma conditions.

2 Atomic Structure Calculations and Classification of the Lines

In these conditions of irradiation, the ions have charge states beyond 20+, and their emission spectrum below 10 Å contains characteristic transitions between upper configurations having one electron with principal quantum numbers larger than 2 and lower levels of the ground complex $(2s+2p)^N$. Since Kelly's compilation [2], the status of the spectra being investigated has remained almost unchanged. For all ions involved, the levels with principal quantum numbers n=2 have been accurately described by Edlén from comparisons along isoelectronic sequences between observed and ab initio MCDF transition energies (n=2, Δn=0) in the vuv region [1]. These "recommended" level values are available for checking the accuracy of theoretical models and approximations. We have used the atomic structure codes of HULLAC [3] based on the relativistic parametric potential method [4] for deriving transition energies and probabilities between full complexes

$$(2)^{N}\text{, i.e. } 2s^{2}2p^{N-2} + 2p^{N}$$

and in opposite parity $2s^{1}2p^{N-1}$

$$(2)^{N-1}3^{1}\text{, i.e.}$$

$$2s^{2}2p^{N-3}3p^{1} + 2s\,2p^{N-3}3d^{1} + 2s^{1}2p^{N-2}3p^{1} + 2p^{N-1}3s^{1} + 2p^{N-1}3d^{1}$$

and in opposite parity

$$2s^{2}2p^{N-3}3p^{1} + 2s^{1}2p^{N-2}3s^{1} + 2s^{1}2p^{N-2}3d^{1} + 2p^{N-1}3p^{1}$$

$(2)^{N-1}4^{1}$ being the same as $(2)^{N-1}3^{1}$ with quantum number 4 instead of 3.

The processing of full complexes is needed to take into account the most important configuration mixing effects. In Table 1, wavelengths, transition probabilities, and combining levels are reported for the prominent lines of the spectrum of carbon-like copper Cu XXIV which had not been reported earlier in the wavelength range 6.9-7.7 Å.

Table 1: Theoretical and observed transitions between complexes of configurations $(1)^{2}(2)^{4}$ and $(1)^{2}(2)^{3}4^{1}$ in carbon-like copper Cu XXIV.

λ_{th} (Å)	gA ($10^{12}s^{-1}$)	E^{o}_{th} ($1000cm^{-1}$)	J^{o}	E^{e}_{th} ($1000cm^{-1}$)	J^{e}	λ_{exp} (Å)	Int (arb.units)
6.9578	23.39	634.6	2.0	15007.0	3.0	6.959	5
7.0341	30.60	1027.6	3.0	15243.9	4.0	7.031	30 Bl XXV
7.1099	23.76	14439.2	3.0	374.4	2.0	7.115	45 Bl XXV
7.1532	21.58	14169.5	2.0	189.7	2.0	7.148	30 Bl XXV
7.1533	27.16	14169.3	3.0	189.7	2.0		
7.1647	21.14	14086.0	2.0	128.6	1.0	7.166	35 Bl XXV
7.3333	21.58	964.9	1.0	14601.3	2.0	7.325	20 w
7.3346	20.24	973.5	2.0	14607.4	3.0		
7.3353	22.63	1170.0	1.0	14802.7	2.0	7.332	15 p
7.3481	44.33	634.6	2.0	14243.5	1.0	7.349	25 p
7.3501	53.83	634.6	2.0	14240.0	2.0		
7.3529	35.89	634.6	2.0	14234.6	3.0		
7.3571	33.06	13592.2	1.0	0.0	0.0	7.354	20 Bl
7.3598	21.17	13777.1	2.0	189.7	2.0		
7.3630	21.52	973.5	2.0	14554.8	1.0	7.359	20 Bl
7.3640	60.58	13769.2	3.0	189.7	2.0		
7.3673	28.14	973.5	2.0	14547.0	2.0		
7.3947	26.77	1027.6	3.0	14550.8	4.0	7.394	40
7.3947	33.10	964.9	1.0	14488.1	2.0		
7.3954	25.10	973.5	2.0	14495.4	3.0		
7.3971	46.76	634.6	2.0	14153.4	3.0		
7.4000	58.38	1027.6	3.0	14541.1	3.0		
7.4032	63.46	1027.6	3.0	14535.3	4.0		

(cont.)							
7.4299	37.31	13587.7	2.0	128.6	1.0	7.427	20
7.4384	20.79	15605.8	1.0	2162.0	1.0		
7.4460	30.14	634.6	2.0	14064.7	3.0	7.446	30
7.4499	116.48	13797.5	3.0	374.4	2.0		
7.4559	96.39	1422.9	2.0	14835.1	3.0	7.459	18
7.4612	25.00	13777.1	2.0	374.4	2.0		
7.4632	51.52	13588.7	3.0	189.7	2.0		
7.4735	32.12	15512.8	1.0	2132.2	0.0	7.471	6
7.4822	24.21	15621.5	2.0	2256.5	2.0		
7.4848	75.11	15617.0	3.0	2256.5	2.0	7.488	6
7.4887	26.99	15362.0	1.0	2008.6	2.0		
7.4888	20.69	1204.1	2.0	14557.4	3.0		
7.4977	23.69	15499.5	2.0	2162.0	1.0		
7.4979	55.99	15345.6	2.0	2008.6	2.0	7.504	5
7.4993	25.85	1170.0	1.0	14504.6	2.0		
7.5029	53.32	15336.8	3.0	2008.6	2.0		
7.5238	36.12	1204.1	2.0	14495.4	3.0	7.520	15
7.5275	32.69	13800.9	1.0	516.2	0.0		
7.5343	32.56	15281.1	3.0	2008.6	2.0	7.53	Bl
7.5365	76.01	1591.0	1.0	14859.8	2.0		
7.5403	29.83	1352.0	1.0	14614.1	2.0		
7.5488	36.41	1027.6	3.0	14274.6	3.0	7.540	25
7.5503	104.59	1027.6	3.0	14272.1	4.0		
7.5505	25.45	15500.7	3.0	2256.5	2.0		
7.5517	23.66	1591.0	1.0	14833.0	1.0		
7.5662	79.44	973.5	2.0	14190.1	3.0	7.556	8
7.6055	38.44	1422.9	2.0	14571.2	2.0	7.600	30 Bl
7.6105	48.55	15301.9	2.0	2162.0	1.0		
7.6135	38.96	1422.9	2.0	14557.4	3.0	7.61	Bl
7.6165	46.00	964.9	1.0	14094.3	2.0		
7.6207	74.37	15130.7	3.0	2008.6	2.0		
7.6253	91.18	15370.8	3.0	2256.5	2.0		
7.6281	60.89	15365.9	2.0	2256.5	2.0	7.62	Bl
7.6308	59.03	15654.3	1.0	2549.6	0.0		
7.6508	33.89	1204.1	2.0	14274.6	3.0		
7.6528	26.94	1204.1	2.0	14271.3	2.0		
7.6900	20.91	15136.1	1.0	2132.2	0.0		

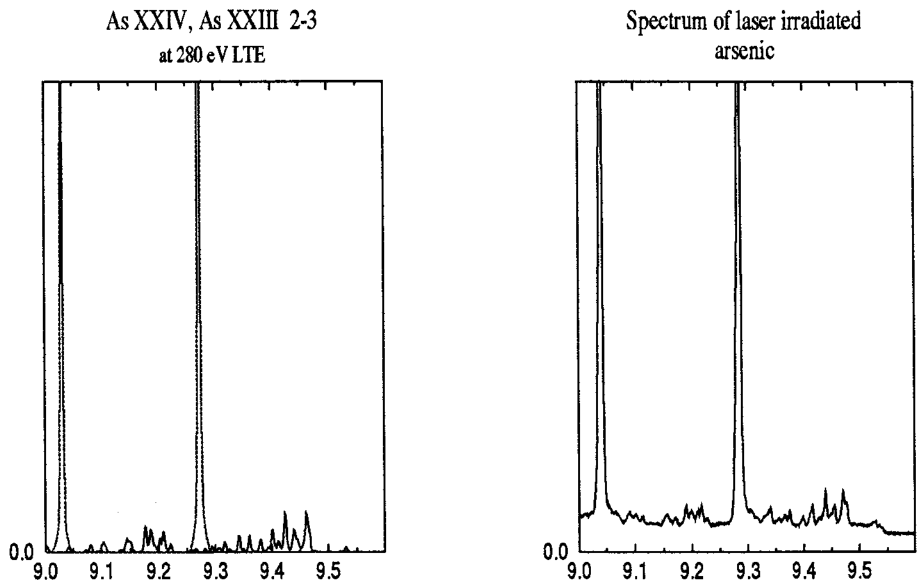

Figure 1: Comparison of observed spectrum of laser-irradiated arsenic (right) with theoretical 2-3 resonance transitions of Ne-like As XXIV and Na-like As XXIII satellites (left). The levels of As XXIII are assumed to be populated according to LTE at 280 eV and not to decay via autoionization. The relative population of As XXIV and As XXIII is an adjustable parameter.

3 Conclusion

Owing to the narrow linewidths and the high signal-to-noise ratio displayed in Fig. 1, the present observations add valuable data to many earlier observations of medium-Z elements. The detailed analysis of these spectra should help in studying ionic charge distribution in laser-produced plasmas. A database with classified lines is under preparation. The ICAMDATA community will be informed when it is available.

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