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Lifetime Measurements in Cu I and Cu II

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Abstract

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Using 180–330 keV Cu^+ ions we have studied the beam-foil spectrum of Cu (1 000–6 000 Å) and determined lifetimes for four excited terms in Cu I and one in Cu II.

1. Introduction

A number of investigations of beam-foil spectra and radiative lifetimes for the 3*d* transition elements have been performed at our laboratory [1]. As part of this program we now report lifetimes for excited terms in Cu I and Cu II. There exists already a wealth of *f*-value data for Cu I, mostly based on emission measurements [2]. For obtaining reliable absolute *f*-values the emission data must usually be normalized by means of lifetime measurements. Only for a very limited number of Cu I levels are accurate lifetime data available.

Lifetimes and *f*-values for the Cu I and Zn I isoelectronic sequences are further of great plasmaphysical significance. Spectroscopic studies of Tokamak plasmas reveal strong impurity lines belonging to these sequences, e.g. highly ionized Mo and W [3]. The transition probabilities of these lines are needed for quantitative measurements of the concentration of these elements. The present study is an introduction to such lifetime work. Additional data, for higher *Z*, can already be found in a beam-foil paper by Andersen et al. [4].

Only one Cu II lifetime is reported here. The Cu II transition studied ($3d^{10}\ ^1S$–$4p\ ^1P$) is the only Cu resonance line in this spectrum with a wavelength longer than the H I Lyman limit. The transition probability will be helpful in the determination of the copper abundance in interstellar dust clouds [5].

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2. Experiment

Copper beams were obtained by inserting CuO into the ion source of the Stockholm 400 kV accelerator and using the CCl_4 method. The beam-foil spectra were studied with a 0.35 m Heath monochromator (2 000–6 000 Å) and a 1 m Seya–Namioka vacuum spectrometer (1 000–2 200 Å) [6]. The lifetimes were measured as described earlier [7]. The data were extracted from the recorded decay curves using standard multi-exponential curve fitting programs. Possible effects due to cascade repopulation were studied using numerical differentiation methods, although cascading was not a serious problem in any of the decay curves measured; all had replenishment ratios [8] of 0.15 or less.

3. Results and discussion

When 200–300 keV Cu^+ beams are used the beam-foil spectra show transitions in Cu I–Cu III. The spectra observed with the Seya–Namioka instrument showed strong Cu II and Cu III transitions, line blending being frequently serious. Above 2 000 Å most lines observed were due to Cu I transitions.

The lifetimes are presented in Table I. Our errors are estimated total uncertainties, including standard deviations, and a 3–4% velocity uncertainty.

The $4p\ ^2P$ term lifetime was measured from both the 3 247 and the 3 274 Å lines, the results being identical within the estimated uncertainties. All decay curves were decomposed into two exponentials. An attempt was made to account for the detailed shape

Table I. *Lifetimes in Cu I and Cu II*

			Lifetime of upper level (ns)		
Spectrum	Transition	Wavelength (Å)	This work	Other experiments	Theory
Cu I	$4s\ ^2S$–$4p\ ^2P$	3 247, 3 274	7.6 ± 0.7 (30)^a	10.9^b; 7.0 ± 0.2^c 7.2 ± 0.3^d; 7.35^e 7.4 ± 0.7^f; 7.1^g	4.9^h; 5.1^i 6.6^j; 7.3^k
	$4s\ ^2S$–$5p\ ^2P$	2 024	12 ± 2	8.7^g; 11^l	
	$4p\ ^2P$–$4d\ ^2D$	5 153, 5 218. 5 220	11 ± 2	10.7^b; 13.1^m	8.9^h; 13.2^j
	$4p'\ ^4F$–$4d'\ ^4G$	3 160–3 307	4.8 ± 0.6 (26)^a	4.5^g	
Cu II	$3d^{10}\ ^1S$–$4p\ ^1P$	1 358	1.8 ± 0.2 (9)^a		

[a] Cascade lifetime.
[b] Riemann [9] emission measurement.
[c] Ney [17] Hanle-effect measurement.
[d] Cunningham and Link [18] phase-shift.
[e] Bell and Tubbs [19] atomic beam.
[f] Andersen et al. [20] beam-foil.
[g] Corliss [12] recommended value.
[h] McGinn [10] SCF calculation.
[i] Stewart and Rotenberg [11] scaled Thomas–Fermi calculation.
[j] Corliss [12] Coulomb approximation calculation.
[k] Siefart et al. [13] semiempirical calculation.
[l] Corliss and Bozman [15] emission measurement.
[m] Kock and Richter [14] emission measurement.

of the 3 247 and 3 274 Å decay curves by incorporating the cascade decay curve from the $4d\ ^2D$ term (5 153–5 220 Å) into the analyses. This study indicated a very low correlation between the $4s$–$4p$ and $4p$–$4d$ decay curves, suggesting that the small cascade repopulation in the $4p\ ^2P$ decay curve must contain appreciable contributions from cascade levels other then $4d$, e.g. $5s$ and $5d$.

The $4d$ lifetime was measured from the 5 218 Å line ($4p\ ^2P_{3/2}$–$4d\ ^2D_{5/2}$). All curves for this decay as well as those for the 2 024 Å line ($4s\ ^2S$–$5p\ ^2P$) could be satisfactorily represented by the sum of one exponential and a small, constant background. The $4d'\ ^4G$ decay time was determined from the 3 307 Å line ($4p'\ ^4F_{9/2}$–$4d'\ ^4G_{11/2}$). Here a two-exponential decomposition was necessary. Cascading was also found for the Cu II $4p\ ^1P$ decay. However, in none of the cases studied has it been possible to assign the cascade decay time to a specific upper level.

In Table I we also compare our results to previous experimental and theoretical data. The present value for the $4p\ ^2P$ level in Cu I agrees well with previous lifetime data. Here the emission study of Riemann [9] seems to have yielded a value that is too long. *Ab initio* calculations, using a pseudopotential Hartree–Fock model [10] or a scaled Thomas–Fermi approximation [11] tend to agree less well with experiments than semi-empirical results, based on the Coulomb approximation [12]. In the calculation of Siefart et al. [13] the wave functions were obtained from fine-structure data. The recommended value of Corliss [12] is based on a critical survey of all Cu I data available in 1970.

The $5p\ ^2P$ lifetime is determined by the $4s$–$5p$, $5s$–$5p$ and $m\ ^2D$–$5p$ transition probabilities. Because of the long wavelength (16 008 Å) the $5s$–$5p$ branch is of little significance, the calculations of McGinn [10] here suggest a transition probability of 1.1×10^7 s^{-1}. The f-values for the $m\ ^2D$–$5p\ ^2P$ doublet (2 618 and 2 766 Å) have been provided by Kock and Richter [14] who used a wall-stabilized arc. In their initial work Corliss and Bozman [15] obtained a $4s$–$5p$ transition rate of 0.3×10^7 s^{-1} whereas Corliss [12] later recommends a more than ten times higher $4s$–$5p$ decay probability. Judging from Table I and assuming the Kock and Richter [41] $m\ ^2D$–$5p\ ^2P$ to be essentially correct, the new $4s$–$5p$ decay rate [12] appears to be too large. Our $4d\ ^2D$ lifetime does not deviate significantly from previous theoretical and experimental results. The $4d'\ ^4G$ lifetime of 4.8 ns is in excellent agreement with the value recommended by Corliss [12]. The latter is based on intensity measurements by Meggers et al. [16].

No comparisons with previous work are possible for the $4p\ ^1P$ lifetime in Cu II. Besides decaying to the $3d^{10}\ ^1S$ ground state the $4p$ level also populates the $4s\ ^3D$ and $4s\ ^1D$ terms. For the $4s\ ^1D$–$4p\ ^1P$ branch Corliss and Bozman [15] give a transition probability of 1.2×10^8 s^{-1}. It is thus clear that the $3d^{10}\ ^1S$–$4p\ ^1P$ resonance transition (1 358 Å) forms the dominating decay mode.

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