Physica Scripta. Vol. 51, 351–353, 1995

Lifetimes of the $4d^9 5p$ Levels in Ag II

R. E. Irving, S. T. Maniak, D. J. Beideck, P. Bengtsson* and L. J. Curtis

Department of Physics and Astronomy, University of Toledo, Toledo, Ohio 43606, U.S.A.

and

R. Hellborg, G. Kalus and I. Martinson

Department of Physics, University of Lund, S-22362 Lund, Sweden

Received September 8, 1994; accepted September 16, 1994

Abstract

We have determined lifetimes of the 12 $4d^9 5p$ fine-structure levels of Ag II, using the beam–foil excitation method. The results are compared with various theoretical predictions. Fairly good agreement is found with recent superposition-of-configurations (SOC) calculations which have included relativistic corrections.

1. Introduction

We have recently reported lifetimes for singly and doubly ionized heavy atoms, Y III [1], Au II [2], Hg II [3] and Hg III [4], obtained by means of the beam–foil excitation technique. Interest in lifetimes and oscillator strengths for such species has strongly increased in recent years, largely because of data needs in astrophysics. For example, observations of high-resolution spectra of the chemically peculiar star χ Lupi, recorded with the Goddard High Resolution Spectrograph (GHRS) on the Hubble Space Telescope (HST) have shown strong overabundances (compared with the solar value) of many such heavy elements [5]. For a quantitative interpretation of the astrophysical observations, a wealth of new, accurate atomic data – theoretical as well as experimental – is needed, including energies, wavelengths, oscillator strengths, lifetimes, hyperfine separations and isotope shifts.

In the present work we have studied transitions in singly ionized silver, Ag II, which belongs to the Pd I isoelectronic sequence. The ground configuration is $4d^{10}$ and the two lowest even configurations are $4d^9 5s$ and $4d^8 5s^2$, whereas the lowest odd configuration is $4d^9 5p$. A schematic energy level diagram is shown in Fig. 1. (Notice that this system is homologous with Au II and Hg III which we have studied previously [2, 4].) From the astrophysical point of view the transitions from the $4d^9 5p$ levels (12 in all) to the four $4d^9 5s$ levels are expected to be relevant, because the wavelengths are in the region which is being studied with the GHRS instrument. We have therefore concentrated on the determination of the lifetimes of the $4d^9 5p$ levels. However, so far no clear evidence has been found concerning Ag II transitions in the spectrum of χ Lupi [6], primarily because the $5s$–$5p$ lines lie in a region which is dominated by strong multiplets belonging to iron-group elements. However, even so the Ag II lifetimes are of potential interest, e.g. in establishing upper limits of the Ag abundance.

2. Experiment

As in our previous studies we used the Danfysik heavy ion accelerator at the University of Toledo [7]. Ions of Ag^+ from the ion source were accelerated to a kinetic energy of 220 keV and directed through a thin carbon foil (2.0–2.4 μg/cm^2 thickness). The light emitted by the foil-excited ions was analyzed with an Acton 1-m normal incidence vacuum monochromator, equipped with a 1200 lines/mm concave grating blazed at 1500 Å. Detailed information about the experimental set up and data-taking methods can be found in published papers [1–4, 8]. As was previously done we took into account the energy loss in the foil and the slight beam divergence after the foil, caused by multiple-scattering processes. The velocity of the foil-excited Ag^+ ions was thereby determined to 0.610 ± 0.015 mm/ns.

In contrast to other techniques such as laser spectroscopy, the beam–foil excitation is not selective, implying that many levels in a given ion can be populated. This leads to cascading which tends to yield apparent lifetimes that are longer than the correct values. An effective way to correct for cascading is provided by the well-known ANDC method

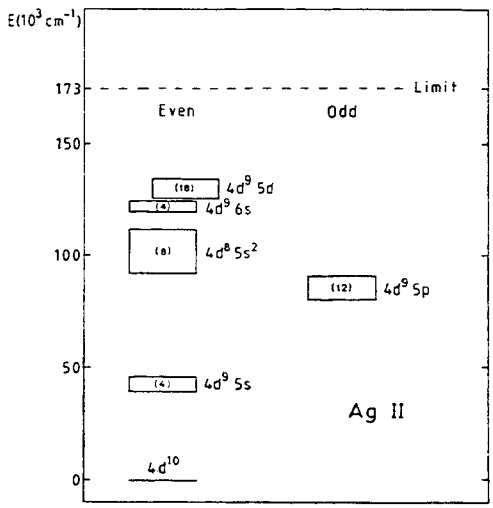

Fig. 1. Schematic energy level diagram for Ag II, showing some low-lying configurations. The number of levels in each configuration is given in par-

* On leave from the Department of Physics, University of Lund.

[9], which involves joint analyses of the decay curve of the level under study and those of higher levels feeding it. This method, which was successfully used in the Y III lifetime study [1], works best when the number of primary cascades is limited, as in the strong yrast chain repopulation in a single valence electron system such as Y III. For Ag II, on the other hand, each $5p$ level can be fed by several higher levels (for instance, all four $6s$ and 10 of the $5d$ levels can decay to a $5p$ level for which J equals 2). Therefore it was necessary here to use the older and less rigorous method which involves fitting the decay curves into sums of exponentials. This procedure was carried out using the program DISCRETE [10]. Because of this circumstance, the uncertainties of the final lifetime values have been substantially increased from the purely statistical errors, so as to take into account cascade contributions which could have eluded the multiexponential fitting analysis.

3. Data analysis and results

A section of a beam–foil spectrum is shown in Fig. 2. This spectrum was recorded with 80 μm monochromator slits which gave a line width (FWHM) of about 1.8 Å. In the wavelength region 1900–2900 Å more than 80 well separated lines were observed, most of which were ascribed to transitions in Ag II. The lines were identified using three early analyses [11–13] and a more recent study [14]. Recently, very accurate wavelengths and relative intensities for Ag II lines have been determined by Kalus [15] who used a Fourier Transform Spectrometer (FTS).

The majority of the lines in our spectra are due to the $5s$–$5p$, $5p$–$5d$ and $5p$–$6s$ transitions in Ag II. Of these, the $5s$–$5p$ lines were by far the most intense. In selecting the lines suitable for lifetime studies, attention was paid to the possibility of line blends. In a few cases the $5s$–$5p$ lines studied could be blended by $5p$–$5d$ transitions, but the latter were generally at least 10 times weaker than the $5s$–$5p$ combinations. We also investigated possible blends from Ag III transitions [16, 17], but even the strongest Ag III lines were faint in our beam–foil spectra.

One typical decay curve is shown in Fig. 3. Using the DISCRETE program the data were here decomposed into two exponentials. Also, most of the other decay curves were approximated by a sum of two exponentials. The results of the lifetime measurements are given in Table I where they are also compared with previous experimental and theoretical data. On the experimental side, Plekhotkina [18] has measured the lifetimes of five $5p$ levels, using the pulsed electron excitation delayed coincidence technique. Three sets of theoretical data are available. Theodosiou [19] has performed semi-empirical, Coulomb Approximation Hartree–Slater (CAHS) calculations for a large number of transitions in Ag II, whereas Kalus [15] has applied the Cowan code [20] to determine theoretical gf-values in Ag II. Recently, Bogdanovich and Martinson [21] have made *ab initio* superposition-of-configuration (SOC) calculations for Ag II and Au II with relativistic corrections added within the Breit–Pauli approximation. A study of Table I shows that the experimental lifetimes obtained in the present beam–foil study are in reasonable agreement with previous experiental data [18], although they are somewhat shorter. Only for the $5p\,^1P_1$ level does a larger discrepancy appear. One explanation could be that this decay time is so short that it could not be observed in the electron excitation study, where the pulse duration was reportedly in the 10–40 ns range [18].

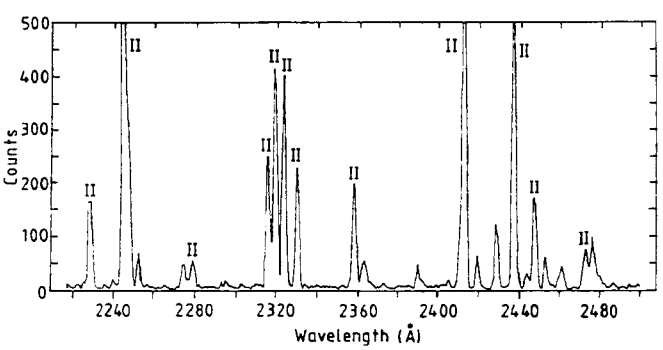

Fig. 2. Partial beam–foil spectrum of Ag, recorded with 220 keV Ag^+ ions. Some of the strongest Ag II lines are indicated. The structure near 2250 Å consists of two strong lines, 2246.4 and 2248.7 Å (see Table I) which were fully resolved at lifetime measurements.

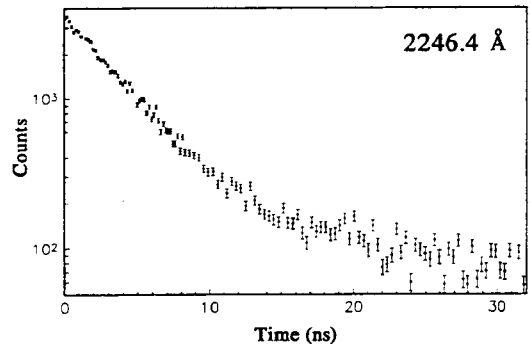

Fig. 3. Intensity decay of the Ag II line at 2246.4 Å ($5s\,^3D_3$–$5p\,^3F_4$).

In contrast to the reasonable agreement with the previous measurement, our experimental lifetimes deviate significantly from the earlier theoretical results [15, 19]. It can also be noted that the two theoretical studies agree with each other, except for the $5p\,^3D_1$ level. Here the explanation is that Theodosiou's calculations are within the LS-coupling scheme, and the "intersystem" transition from $5p\,^3D_1$ to the $4d^{10}\,^1S_0$ ground term has not been taken into account.

The calculations by Kalus [15] were performed with a fairly small number of configurations which may imply large uncertainties in some cases. For instance, there can be a strong interaction between the $4d^9 5p$ and $4d^8 5s5p$ configurations, and here the energies of most of the levels belonging to $4d^8 5s5p$ are not known for Ag II.

Our experimental data agree better with the elaborate recent calculations [21], although even here the theoretical lifetimes are systematically shorter. This improved agreement demonstrates that configuration interaction indeed plays an important role for Ag II and quite extensive calculations are obviously needed for obtaining reliable results.

In discussing shortcomings on the experimental side we have mentioned the problems due to cascading which could not be accounted for in a rigorous way. However, as already noted, the $5p$–$5d$ and $5p$–$6s$ lines were usually considerably weaker than the $5s$–$5p$ transitions studied, which increases the confidence in the experimental results. As a further check, we also measured the decay times of the Ag I resonance doublet $5s\,^2S$–$5p\,^2P$ (3230.68 and 3382.89 Å), obtaining values that were about 15% longer than the accurate experimental data of Carlsson *et al.* [22] who performed time-

Table I. *Lifetimes of the $4d^9 5p$ levels in Ag II*

Level	Energy (cm^{-1})	Wavelength (Å)	Lifetime (ns)				
			Experiment		Theory		
			a	b	c	d	e
$5p\,^3P_2$	80 176	2437.8	4.2 ± 0.7	4.8 ± 0.7	2.853	2.540	2.999
$5p\,^3F_3$	82 171	2413.2	4.1 ± 0.5	4.7 ± 0.5	2.642	2.465	3.200
$5p\,^3P_1$	83 625	2331.4	3.4 ± 0.6	3.9 ± 0.2	2.350	1.915	2.439
$5p\,^3F_4$	83 669	2246.4	3.3 ± 0.4		2.193	2.049	2.738
$5p\,^3D_2$	85 200	2248.7	3.7 ± 0.6		2.102	1.870	2.876
$5p\,^3P_0$	86 140	2357.9	2.6 ± 0.6		2.539	2.293	2.823
$5p\,^3D_3$	86 460	2113.8	3.4 ± 0.6	3.7 ± 0.2	1.849	1.842	2.585
$5p\,^3F_2$	86 888	2317.1	3.8 ± 0.6		2.441	2.190	3.049
$5p\,^1F_3$	89 134	2065.9	3.4 ± 0.7		2.349	2.084	2.869
$5p\,^1P_1$	89 895	2280.0	1.2 ± 0.4	4.5 ± 0.2	0.571	0.514	0.791
$5p\,^3D_1$	90 334	2145.6	2.9 ± 0.6		1.953	0.778	1.482
$5p\,^1D_2$	90 887	2229.5	3.3 ± 0.7		2.086	2.231	2.623

a = This work; b = Ref. [18]; c = Ref. [19]; d = Ref. [15]; e = Ref. [21].

resolved laser spectroscopy. This discrepancy can largely be explained by cascading which affected our measurement but was absent in the laser work. (The $5p\,^2P$–$5d\,^2D$ multiplet is quite intense in beam–foil spectra). We may therefore assume that the neglect of rigorous cascade corrections will introduce a similar uncertainty also for the Ag II transitions. In view of this circumstance, there is satisfactory agreement between the present experimental data for Ag II and the new theoretical data [21].

Acknowledgements

We are grateful to Profs. Se. Johansson and C. E. Theodosiou and Dr. G. M. Wahlgren for valuable discussions and advice. Three of the authors (P.B., R.H. and I.M.) are grateful for the hospitality extended to them at the University of Toledo. They also acknowledge travel grants from the Royal Physiographic Society, Lund. L.J.C. and S.T.M. are supported by the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Chemical Sciences. The Swedish participants are supported by the Swedish Natural Science Research Council and the Swedish National Space Board.

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