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Lifetimes of the $4d^9 5p$ Levels in Cd III

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Abstract

Lifetimes are reported for the twelve $4d^9 5p$ fine structure levels of Cd III, measured using beam-foil excitation. Isoelectronic trends are studied through comparisons with earlier measurements for Ag II, Irving, R. E. *et al.*, Physica Scripta **51**, 351 (1995).

1. Introduction

We report here lifetime measurements in Cd III, the latest in a series of studies in this laboratory of few times ionized members of isoelectronic sequences with nd^{10} ground configurations. Earlier studies have treated Au II [1] and Hg III [2] in the $n = 5$ Pt sequence and Ag II [3] in the $n = 4$ Pd sequence. Cd III is isoelectronic to Ag II and homologous to Hg III.

The study of lifetimes in singly and doubly ionized heavy atoms has been stimulated by the observation of such systems in vacuum ultraviolet stellar spectra obtained with the Goddard High Resolution Spectrograph aboard the Hubble Space Telescope [4]. Here, the spectra of certain classes of chemically peculiar stars have been found to exhibit large enhancements in abundances and isotopic ratios for certain heavy elements [4], and reliable oscillator strength data are required for quantitative interpretation of these observations. In addition, surveys of the skies are being carried out to identify sources of extreme ultraviolet (EUV) radiation shortward of 912 Å (using, e.g., the Extreme Ultraviolet Explorer (EUVE) satellite), which will permit EUV absorption spectroscopy of the interstellar medium [5]. Interpretation of these data will require a knowledge of oscillator strengths in heavy ions for transitions that are connected to the ground state.

In a recent study [6] of the abundances Pt, Au and Hg in the chemically peculiar HgMn-type stars κ Cancri and χ Lupi, the resonance doublet of Cd II was identified in χ Lupi. The same study [6] indicated that in χ Lupi the abundance of Hg III (homologous to Cd) is 1.23 dex higher than that of Hg II. Thus, although the enhancement over the solar abundance in these stars is much greater for Hg than for Cd, the observation of Cd II suggests that Cd III might also be measurably present in stars at the effective temperature of χ Lupi (10 650 K) or higher.

For Cd III the ground configuration is $4d^{10}$, the two lowest excited even configurations are $4d^9 5s$ and $4d^8 5s^2$, and the lowest odd configuration is $4d^9 5p$. Since there are no odd levels below them in energy, the $4d^9 5s$ levels are very long-lived, would require ion traps or cooler rings for their measurement, and would be collisionally quenched except in very tenuous plasmas. The next set of levels, the $4d^9 5p$, is the object of this study, and only the $J = 1$ levels can make (spin-mixed) dipole-allowed transitions to the ground state. Cascade transitions into $4d^9 5p$ from the $4d^8 5s^2$ levels were not observed with any reasonable strength in our beam-foil spectra. Indeed, the only other transitions that were seen with significant strength were from the $4d^9 5d$ levels and, due to blending with other levels and their own weakness, we were able to measure the lifetime of just one of the 18 levels. Only one theoretical computation of an oscillator strength in Cd III is presently available, and that involves an investigation [7] of theoretical subtleties in the $4d^{10}\ {}^1S_0$–$4d^9 4f\ {}^1P_1$ resonance transition of the Pd isoelectronic sequence. A search for this transition in our beam-foil spectra in the vicinity of 428 Å indicated no significant intensity in either first or second order with our normal incidence vacuum ultraviolet (VUV) monochromator.

2. Experiment

This experiment was conducted utilizing the University of Toledo Heavy Ion Accelerator [8, 9]. Ions of Cd^+ and Cd^{++} were produced in the ion source and magnetically analyzed and post-accelerated to energies ranging from 240 to 260 keV for Cd^+ and to an energy of 520 keV for Cd^{++}. The ions were then steered through a thin carbon foil (2.1–2.5 $\mu g/cm^2$ thickness) which produced excitations primarily in Cd II and Cd III for the lower energies, and primarily in Cd III and Cd IV for 520 keV. The light emitted by the excited ions was analyzed with an Acton 1-m normal incidence VUV monochromator, with three sets of concave gratings and detectors: a 600 l/mm grating coupled with a bialkali detector for transitions from the $5p\ {}^3P_2$ and $5p\ {}^3F_2$ levels, a 2400 l/mm grating coupled with a channeltron detector for the three $J = 1$ ground state transitions, and a 1200 l/mm grating coupled with a solar blind detector for the remainder of the levels ($\lambda = 1500$–1800 Å in Table I). The post foil velocity was determined to within 2.5% by taking into account uncertainties in energy calibration, foil thickness, and possible beam divergence. For the Cd^+ beams the velocities ranged from 0.617 mm/ns (240 keV beam and 2.5 $\mu g/cm^2$ foil) to 0.647 mm/ns (260 keV beam and 2.1 $\mu g/cm^2$ foil), whereas for the Cd^{++} beam the velocity was around 0.91 mm/ns, again varying slightly with individual foil thickness.

Using the Danfysik Model 911A ion source, ions were obtained from the chemical compound CdS, with Argon used as the carrier gas. In order to avoid rapid foil breakage, the current of Cd^+ was kept to 100 nA or less. A current of 25–50 particle nA could be obtained for the Cd^{++} beam. Since this is the first time that doubly charged ions have been obtained from the ion source of this accelerator, a brief discussion of the procedures by which they were generated is appropriate. To obtain Cd^{++}, the anode voltage was set at 50–60 volts. Raising the anode power

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

Level	λ(Cd III) Å	τ(Cd III)[a] ns	τ(Ag II)[b] ns	τ(Cd III) /τ(Ag II)
$5p\ ^1P_1$	684.6	0.41 ± 0.07	1.2 ± 0.4	0.34 ± 0.17
$5p\ ^1D_2$	1768.8	1.93 ± 0.21	3.3 ± 0.7	0.58 ± 0.19
$5p\ ^1F_3$	1523.6	1.66 ± 0.19	3.4 ± 0.7	0.49 ± 0.16
$5p\ ^3P_0$	1789.2	1.99 ± 0.22	2.6 ± 0.6	0.77 ± 0.26
$5p\ ^3P_1$	720.7	1.63 ± 0.13	3.4 ± 0.6	0.48 ± 0.12
$5p\ ^3P_2$	1874.1	2.47 ± 0.21	4.2 ± 0.7	0.59 ± 0.15
$5p\ ^3D_1$	677.4	1.08 ± 0.14	2.9 ± 0.6	0.37 ± 0.10
$5p\ ^3D_2$	1678.1	1.71 ± 0.17	3.7 ± 0.6	0.46 ± 0.12
$5p\ ^3D_3$	1601.6	1.71 ± 0.21	3.4 ± 0.6	0.50 ± 0.15
$5p\ ^3F_2$	1844.7	2.30 ± 0.39	3.8 ± 0.6	0.61 ± 0.20
$5p\ ^3F_3$	1793.4	2.48 ± 0.28	4.1 ± 0.5	0.60 ± 0.14
$5p\ ^3F_4$	1707.2	1.99 ± 0.18	3.3 ± 0.4	0.60 ± 0.13

[a] This work.
[b] Irving *et al.*, Ref. [3].

leads to an increase in the anode voltage and the anode current, resulting in a greater production in both singly and doubly charged ions. A lowering of the filament current then results in an increase in the anode voltage and a decrease in the anode current. In optimizing the doubly charged current, the doubly charged portion of the discharge may be larger when the total discharge is actually smaller. Also, the filament current must be kept high enough to maintain the gas support beam, but the optimum yield is very close to this cut-off current. It was also found that a filament slightly thicker than that manufactured by Danfysik (0.75 ± 0.01 mm rather than 0.70 ± 0.01 mm) yields a larger Cd^{++}/Cd^{+} ratio, and such a filament lasts about twice as long.

While the beam-foil method is applicable to virtually any charge state of any atom, its energy level excitation is not selective. Thus many levels are populated upon passage through the exciter foil, leading to cascade replenishment of the population of each decaying level. If not correctly accounted for, multiexponential fits have been known to yield overestimates of the lifetimes. An effective way to correct for cascading is to make use of the ANDC method [10], which involves joint analysis of the decay curves of the level studied and those which directly repopulate it. This method works best when cascading channeled though a few strong direct transitions, such as the yrast chain in a single valence electron system. However Cd III, like Ag II [3] and the homologous systems Au II [1] and Hg III [2], have many direct cascades of similar strength which are not all amenable to measurement. Thus ANDC methods could not be applied here, and it was necessary to use multi-exponential curve fitting methods. This procedure was carried out using the nonlinear least squares multi-exponential fitting program DISCRETE [11]. Since the ANDC method not only increases the precision of the determination, but also provides an internal check of the correctness of the interpretation, the use of curve fitting methods introduces additional non-statistical uncertainties that must be carefully assessed. The uncertainties in our multi-exponential fits were computed by combining statistical uncertainties in the individual fits, scatter among the independent measurements, uncertainties in the beam velocity, and estimates of possible errors introduced by cascade corrections.

3. Data analysis and results

A survey spectrum in the channeltron region, displaying the three $J = 1$ ground state transitions, is shown in Fig. 1. The lifetimes of all twelve $4d^9 5p$ levels were measurable in at least one unblended decay channel. Lines from Cd IV [12] were either very weak or totally absent in the 240–260 keV energy spectra, indicating that such blends pose no problem. Blendings with Cd II [13] were sufficiently rare that we could avoid the use of any line that might possess such a blending problem. We utilized the classification work of van Kleef *et al.* [14] to identify our Cd III spectrum, of Shenstone and Pittenger [13] for Cd II, and of Joshi *et al.* [12] for the Cd IV spectrum. In the 520 keV spectrum (in contrast to the results at 240–260 keV), Cd IV lines were very prevalent, indeed as strong or stronger than Cd III lines in some instances. We measured decay curves for all 12 levels using the 260 keV energy range, and utilized the 520 keV beam for only one of the levels that was particularly difficult for curve fit analysis.

For all of the decay curves we were able to obtain a suitable fit using one to three exponentials. The lifetimes extracted for these levels are given in Table I. For all except the $4d^9 5p\ ^1P_1$, the first exponential was short-lived and intense, and the second (and third for two cases) were long-lived and weak (5 to 100 times longer and 1/10 as intense as the first exponential). A typical measurement of the decay curve for the $4d^{10}\ ^1S_0$–$4d^9 5p\ ^1P_1$ transition at 684.6 Å is shown in Fig. 2. This $4d^9 5p\ ^1P_1$ decay curve required special care because (similar to the corresponding cases observed in Au II [1], Hg III [2] and Ag II [3]), its primary and second exponentials were commensurate (the second exponential being about 4 times the lifetime and 1/4 the intensity of the primary), with a longer-lived and weaker third component. To rule out blending with other charge states, decay curves of this transition were measured at both 260 keV and 520 keV, and both yielded equivalent decay curves.

The corresponding values for the lifetimes in Ag II [3] are also listed in Table I, and the ratio of the Cd III and Ag II lifetimes are also given for comparison. Note that, because they involve ground state transitions, all three $J = 1$ levels in both Cd III and Ag II are shorter-lived than the other levels, with the $5p\ ^1P_1$ being much shorter-lived. An exten-

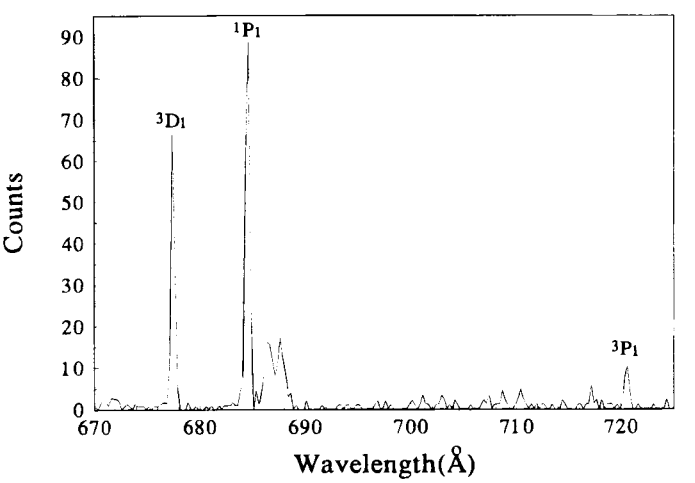

Fig. 1. Spectrum in the channeltron region. The three $J = 1$ ground state transitions from the $4d^9 5s\ ^3D_1$, $^1P_1$ and $^3P_1$ levels are seen at 677.4, 684.6 and 720.7 Å.

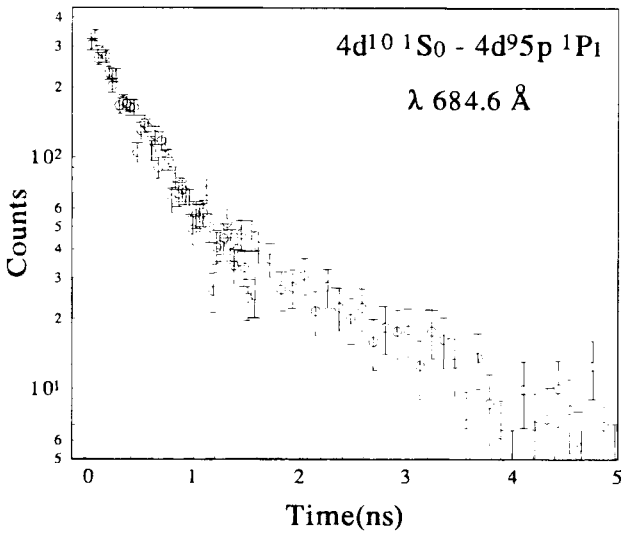

Fig. 2. Decay curve for the $4d^95p\ ^1P_1$ measured at 684.6 Å.

sion of this study to In IV is underway to further elucidate these trends. As indicated above, we also measured the decay of one the $4d^95d$ levels, and our lifetime determination for the $4d^95d\ ^1D_2$ level, measured at 1507.0 Å, yielded 3.3 ± 0.3 ns.

4. Conclusion

We have determined the lifetimes of all twelve levels of the $4d^95p$ configuration of Cd III. The results show relative consistency with earlier measurements of Ag II [3], the next lower member of the Pd isoelectronic sequence, as can be seen from the ratio τ(Cd III)/τ(Ag II) presented in Table I. Although no theoretical comparisons are available for Cd III, comparisons with theory have been made for the Ag II data [3]. These indicate that the experimental lifetimes are somewhat longer than the theoretical calculations. These discrepancies decrease, but do not disappear, as increasingly elaborate theoretical methods are utilized, and indicate the need for addition study. On the experimental side, the degree to which cascade effects have been accounted for can be tested by isoelectronic comparisons, since the primary and cascade lifetimes often scale differently with nuclear charge. The isoelectronic trends determined here are being further examined in a study of In IV that is currently in progress.

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