

Lifetimes of the $4d^95p$ levels in In IV

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Abstract

Lifetimes are reported for the twelve levels of the $4d^95p$ configuration in Pd-like In IV, measured using beam-foil excitation. Isoelectronic trends are studied through comparisons with earlier measurements for Cd III and Ag II.

1. Introduction

We report here lifetime measurements of the $4d^95p$ levels in In IV. This is 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 the isoelectronic ions Ag II [1] and Cd III [2] of the $n = 4$ Pd sequence as well as the homologous ions Au II [3] and Hg III [4] in the $n = 5$ Pt sequence.

As is characteristic for this sequence, the first excited configuration of In IV is the $4d^95s$, which has the same even parity as the $4d^{10}$ ground state, and the levels are thus metastable to dipole-allowed E1 decay. The lowest set of odd parity levels, the $4d^95p$, are the object of this study. For this configuration, only the $J = 1$ levels 1P_1 , 3P_1 and 3D_1 can make E1 transitions to the 1S_0 ground state, but all twelve levels can decay to the $4d^95s$ levels. The populations of the $4d^95p$ levels are replenished by cascade transitions from the $4d^85s^2$, $4d^95d$, and $4d^96s$ levels. Although they could be identified in our spectra, the intensities of these transitions into $4d^95p$ were at least one order of magnitude less than those out of the $4d^95p$ levels. This is similar to the results obtained in our earlier studies in Ag II [1] and Cd III [2]. Since these lines were not only weak, but often were blended with lines within 0.3 \AA or closer, it was not possible to make reliable measurements of their decay curves. No theoretical calculations of the lifetimes of these levels are available, and the only computation of an oscillator strength in In IV involves an isoelectronic investigation [5] of theoretical subtleties in the $4d^{10}1S_0-4d^94f^1P_1$ resonance transition of the Pd sequence. A search for this transition in our beam-foil spectra was made in second order, and revealed three extremely dim candidates within the predicted wavelength region near 300 \AA .

2. Experiment

This experiment utilized the University of Toledo Heavy Ion Accelerator, and detailed descriptions of this facility are provided in the reports of earlier studies in this series [1–4], and in instrumentation reviews [6, 7]. Ions of In^{2+} and In^{3+} were produced in the ion source, accelerated through 20 kV, and magnetically analyzed. After momentum and mass-to-charge selection, the ions were post-accelerated to final energies of 480 keV (for In^{2+}) and 780 keV (for In^{3+}). The ions then entered an electrostatic switchyard and were steered into the experimental station and collimated before

passage through a thin carbon foil (ranging from 2.1–2.5 $\mu\text{g}/\text{cm}^2$).

At beam energies of 480 keV, the observed spectroscopic excitations were primarily in In II, In III and In IV. The 780 keV energy was used to measure only one transition that was in a region free of In V lines, and the charge states produced there were not studied in detail. No significant presence of In V was observed in the spectra at 480 keV, and the In I transitions lie outside the wavelength region of interest (460–1815 \AA).

The In IV emission lines were analyzed with an Acton 1-m normal incidence VUV monochromator, with two sets of concave gratings and detectors: a 24001/mm grating coupled with a channeltron detector for the three $J = 1$ transitions; a 12001/mm grating for the other nine transitions. The post foil velocity was determined to within 2.5% by taking into account uncertainties in energy calibration, foil thickness, and possible beam divergence. The post-foil velocity was 0.88 mm/ns for the In^{2+} runs and 1.13 mm/ns for the In^{3+} run.

Using the Danfysik Model 911A ion source, ions were obtained from pure indium metal. No carrier gas was necessary, but there was a tendency for the metal to melt and plug the gas inlet jet. To remedy this problem, a fitting was constructed to insert against the high temperature oven to protect the jet from clogging. To minimize foil breakage, the current was limited to less than 200 nA (100 particle nA for In^{2+}). It was relatively easy to produce In^{2+} currents greater than 200 nA, and it was possible to obtain currents approaching 1 μA . A current of about 10 nA (≈ 3 particle nA) of In^{3+} could be obtained, which is sufficient (albeit time-consuming) to permit reliable measurements. The system is presently being upgraded to permit multiplexed measurement using position-sensitive detection methods. This can greatly increase the efficiency of data collection, and in the near future we expect that the use of such low currents will not only be feasible, but will be the rule rather than the exception. The methods used to obtain doubly and triply charged indium in the ion source are similar to those used earlier for obtaining Cd^{2+} , and are discussed in Ref. [2].

Due to the nonselective nature of beam-foil excitation, the level populations (and thus the decay curves) so-produced are affected by cascade replenishment. Thus, whenever possible, it is desirable to make lifetime measurements using the ANDC method [8], which performs a joint analysis of the decay curves of the level of interest together with those of levels that directly repopulate it. This method lends itself well to systems where there are a few strong direct transitions, such as the yrast chain in a single valence electron system. However, in In IV and the other nd^{10} systems we have studied, there are many direct cascades of similar

strength that are not all amenable to measurement. Even if all of the measurements were possible, the statistical accuracy would not be sufficient, due to the sheer number and relative weakness of the cascading levels. Thus, the ANDC method could not be applied here and, as in our earlier investigations of these systems, it was necessary to use multiexponential curve fitting methods.

This fitting procedure was carried out using the nonlinear least squares multiexponential fitting program DISCRETE [9], ported to a Linux workstation running on a 120 MHz Pentium processor. Since curve fitting of individual decay curves does not possess the internal consistency checks inherent in the correlated decay curve analysis of the ANDC method, additional nonstatistical errors are possible which must be carefully assessed. The uncertainties in our multiexponential fits were computed by combining statistical uncertainties in the individual fits, scatter among the independent measurements, uncertainties in the beam velocity, estimates of the influence due to blending (in the three cases for which blending was unavoidable), and estimates of possible errors introduced by cascade corrections.

3. Data analysis and results

A survey spectrum in the channeltron region, displaying the three $J = 1$ resonance transitions, is shown in Fig. 1. The lifetimes of nine of the twelve $4d^95p$ levels were measurable in at least one completely unblended decay channel. Lines from In V were essentially absent from the spectra, and no positive identifications within this charge state could be made. In each of the three cases for which no unblended transitions from the upper level were available, the separation between the centers of the two blended lines was sufficient to produce a variation in the exponential content of the admixture of decay curves when measured as a function of wavelength across the line profile.

Through a comparison of decay curves obtained in different off-center wavelength slices taken over the line, the effects of blending can be removed [10]. In two of the three cases, namely the $4d^95p^1F_3$ and $4d^95p^3P_2$ levels, the separation was 0.5–0.6 Å, which is just at the limit of our spectral resolution. Thus, the Gaussian tail of one overlaps the other, and by measuring decay curves at several positions off center and away from the blend, it was possible observe the reduction and disappearance of the exponential

components arising from the unwanted line. In the case of the $4d^95p^1F_3$, the blend was with the $4d^95p^3F_2$ level, which had a lifetime of 1.67 ns (which we measured separately in an unblended channel). This suggests that our fitted value of 1.30 ns may slightly overestimate the lifetime due to the influence of the blend. In the case of the $4d^95p^3P_2$, the blend was with the $4d^95s^2^2D_{3/2}$ transition in In III, which has a lifetime of 2.2 ns [11]. Measurements on either the long or short wavelength side of the line yielded the same exponential content, but with differing admixtures. Moreover, this decay curve required at least three exponential components to obtain an adequate fit, and two of the exponentials were quite close to each other. Thus, our fitted result for this case may slightly overestimate the true lifetime. The last of the blended levels was the $4d^95p^3F_4$ transition; this was possibly blended by an In II line, the $5s7d^1D_2$ transition that was 0.2 Å away. It was for this transition that we supplemented our measurements with a run with the triply ionized beam. The measurements at 780 and 480 keV agreed reasonably well, indicating that the effects of blending were probably weak.

To identify our In IV spectrum, we relied on the energy level calculations of Bhatia and Jones [12], using the classification work of Bhatia [13, 14] for the $4d^95p$ levels, and the classification work of van Kleef and Joshi [15] for the $4d^95p$, $4d^25s^2$ and $4d^26s$ levels. To identify possible blends with In III, we used the spectroscopic identifications of Bhatia [16], and to identify blends in In II, we used the energy levels of Paschen and Campbell [17] as critically compiled by Moore [18]. Since the spectroscopic data in Bhatia's Thesis [14] are not conveniently accessible, we have quoted the wavelengths from that source to their full accuracy in Table I.

For all of the decay curves, we were able to obtain a suitable fit using two to three exponentials. The lifetimes for these levels are given in Table I. As in Cd III, all levels except the $4d^95p^1P_1$ had a first exponential that was short-lived and intense, and a second (and in some cases a third) exponential that was long-lived and weak (5 to 100 times longer and with 1/10 or less the intensity of the first exponential). A typical measurement of the decay curve for the $4d^95p^3F_3$ level at 1472.3 Å is shown in Fig. 2. As in the past cases, the $4d^95p^1P_1$ decay curve required special care because its primary and secondary exponentials were commensurate (the second exponential being about 4 times the

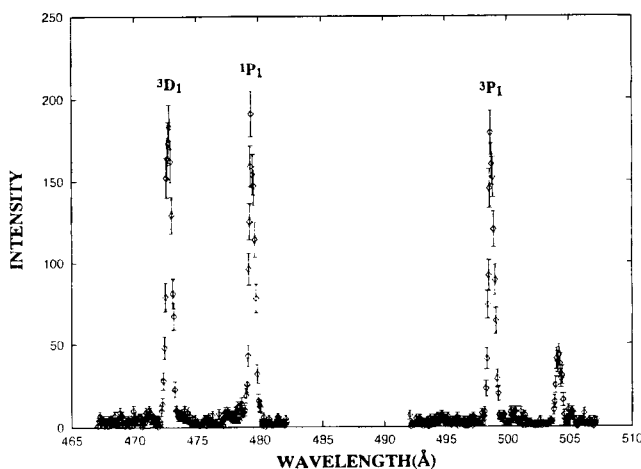


Fig. 1. Spectrum in the channeltron region. The three $J = 1$ transitions $4d^95p^1P_1$, 3P_1 and 3D_1 are seen at 472.7, 479.4, and 498.6 Å.

Table I. Lifetimes of the $4d^95p$ levels in In IV and Cd III.

Level	λ (In IV)	τ (In IV) ^a	τ (Cd III) ^b	τ (In IV)/ τ (Cd III)
$4d^95p^1P_1$	479.390	0.26 ± 0.05	0.41 ± 0.07	0.63 ± 0.21
$4d^95p^1D_2$	1439.663	1.46 ± 0.15	1.93 ± 0.21	0.76 ± 0.16
$4d^95p^1F_3$	1406.082	1.30 ± 0.19	1.66 ± 0.19	0.78 ± 0.18
$4d^95p^3P_0$	1446.000	1.58 ± 0.18	1.99 ± 0.22	0.79 ± 0.15
$4d^95p^3P_1$	498.617	1.29 ± 0.14	1.63 ± 0.13	0.79 ± 0.15
$4d^95p^3P_2$	1533.457	1.67 ± 0.19	2.47 ± 0.21	0.68 ± 0.14
$4d^95p^3D_1$	472.708	0.71 ± 0.13	1.08 ± 0.08	0.66 ± 0.15
$4d^95p^3D_2$	1351.025	1.18 ± 0.18	1.71 ± 0.17	0.69 ± 0.17
$4d^95p^3D_3$	1333.862	1.19 ± 0.13	1.71 ± 0.21	0.70 ± 0.14
$4d^95p^3F_2$	1509.819	1.67 ± 0.17	2.30 ± 0.39	0.73 ± 0.20
$4d^95p^3F_3$	1521.605	1.78 ± 0.15	2.48 ± 0.28	0.72 ± 0.14
$4d^95p^3F_4$	1381.784	1.36 ± 0.14	1.99 ± 0.18	0.68 ± 0.13

^a This work.

^b Henderson *et al.*, Ref. [2].

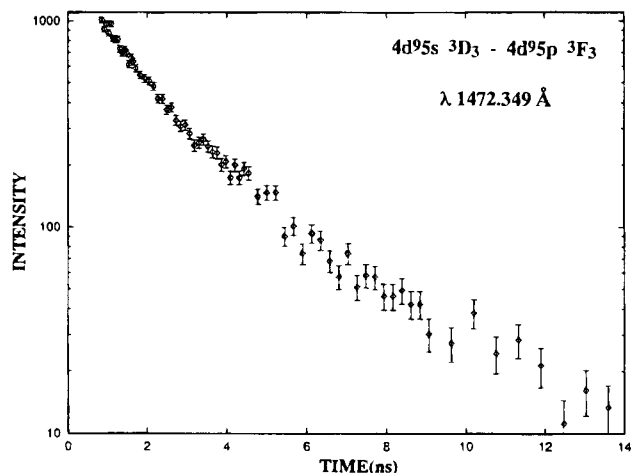


Fig. 2. Decay curve of the $4d^9 5p \ ^3F_3$ level measured in the transition to $4d^9 5s \ ^3D_3$ at 1472.3 \AA .

lifetime, and 1/3 the intensity of the primary), with a longer-lived and weaker third component. The determination is also hampered by the shortness of the lifetime, giving us an accuracy of only 15%.

The values for the corresponding lifetimes in Cd III [2] are also listed in Table I, as is the ratio between the lifetimes in In IV and Cd III. All twelve transitions have similar ratios, averaging 0.72 (which compares closely with the reciprocal ratio of their ionization stages, 0.75). In light of our ability to produce a significant amount of triply ionized atoms, this study may be extended to Sn V when the implementation of our multiplexed position-sensitive detection system has been completed.

4. Conclusion

We have determined the lifetimes of all twelve levels of the $4d^9 5p$ configuration in In IV. An isoelectronic comparison

with earlier measurements for Cd III [2] and Ag II [1], the next two lower members of the Pd sequence, indicates clear regularities and consistent relative trends. The ratio of $\tau(\text{In IV})/\tau(\text{Cd III})$ suggests that the results have an approximately linear scaling with ionicity.

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