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Lifetimes for Low-lying Levels in Zn I and Zn II

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Abstract

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Lifetime measurements using the beam-foil technique have been made for levels in Zn I and Zn II. The following results (in ns) were obtained: *Zn I,* $4s4p\ ^1P$ (1.33 ± 0.07), $4s4d\ ^1D$ (20.5 ± 1.5), $4s4d\ ^3D$ (5.4 ± 0.6); *Zn II,* $4p\ ^2P$ (2.07 ± 0.20), $4d\ ^2D$ (1.40 ± 0.15), $5s\ ^2S$ (1.8 ± 0.2), $5p\ ^2P$ (17 ± 2). These results are compared with previous experimental and theoretical results and the origins of certain disagreements are analyzed.

1. Introduction

The radiative lifetimes and oscillator strengths in the Cu I and Zn I isoelectronic sequences have attracted much interest in recent years. The $\Delta n = 0$ resonance lines in Cu-like Mo XIV and Zn-like Mo XIII have been observed in Tokamak plasmas [1, 2] and the corresponding f-values are vital for plasma-physical studies of impurity concentrations and radiative energy losses.

However, the f-values in Cu I and Zn I and their isoelectronic sequences are also quite interesting from the atomic-structure point of view. Theoretical analyses by Froese Fischer [3] show the importance of configuration mixing for the Cu I sequence $4s$–$4p$ f-values. In Zn II, for example, the Hartree–Fock f-value is reduced by more than 30% if correlations are included in the calculations. Recently, Shorer and Dalgarno [4] as well as Froese Fischer and Hansen [5] have theoretically investigated the Zn I sequence. The results show that the f-values are not only affected by the correlation between the two valence electrons but also – to a significant degree – by the interaction with the $3d^{10}$ subshell.

A comparison between theoretical and experimental f-values for resonance lines in the Cu I and Zn I sequences shows that there is good agreement for the neutral atoms. However, for Zn II and Ga II certain discrepancies between theoretical and experimental f-values (the latter usually originating from beam-foil studies) already begin to appear. For higher spectra the gap between theoretical and beam-foil f-values widens. Because the theoretical work is considered to become more reliable with increasing nuclear charge in an isoelectronic sequence it is usually believed that the present discrepancy is largely due to shortcomings on the experimental side. The beam-foil excitation is not a selective one and the measured decay curves are generally rather complex because of cascading processes. Several authors, e.g., Younger and Wiese [6] emphasize that improper analyses of the experimental decay curves may be responsible for most of the deviations from the theoretically expected values. The reliability of the beam-foil method when applied to resonance transitions in relatively heavy atomic systems has actually been questioned. It is therefore of interest to perform new measurements with this technique with emphasis on studying and minimizing effects of cascading decays.

In the present paper we report one such study for selected levels in Zn I and Zn II. Special care was taken to ensure good counting statistics, and the measurements were performed at a number of different beam energies. Several analytical and numerical techniques were used for decay-data analysis.

2. Experiment

We used the 400 kV ion accelerator [7] at the Research Institute of Physics in Stockholm to accelerate Zn^+ ions to 180–300 keV energies. The radiation from foil-excited Zn atoms and ions was studied with a 35 cm Heath EUE-700 monochromator, equipped with a Peltier-cooled EMI 9789 photo-multiplier.

It was easy to obtain beam currents of several μA through the 4 mm diameter foil. In order to reduce foil damage much lower currents were used, however. Most measurements were performed with 0.2–0.4 μA beams.

The lifetimes were measured by selecting a given line and moving the foil in discrete steps (1/8 or 1/4 mm) along the direction of the beam. An optical normalization technique was used in which a photomultiplier tube viewed the beam at a fixed distance from the foil through a fibre optics light guide. This technique compensated for beam fluctuations during data taking.

The lifetime measurements were automated with the foil motion being achieved by a stepping motor and a programmable control unit [8]. Each decay curve consisted of 150–200 data points which were stored in an Intertechnique 4000 channel analyzer, operated in the multiscaling mode. The velocity of the particles after the foil was determined with a Danfysik 50 cm radius 90° electrostatic analyser which was mounted at the end of the target chamber. The analyser was calibrated with the 658 MHz quantum beats of the He I line at 3889 Å ($1s2s\ ^3S$–$1s3p\ ^3P$). All lifetime measurements were carried out at several ion velocities and using a number of foil thicknesses. For details concerning the experimental procedure we refer to [9].

After background correction the decay data were analyzed using the computer program DISCRETE [10]. This fitted each decay curve to one or more exponentials, giving also the "best" and "next best" solution. These results were further compared with hand-fits of the decay curves, and the difference was usually found to be very small. Such curve-fitting is reliable as long as the primary and cascade lifetimes are sufficiently different from each other. Tests were also made using deliberately poorer statistics, e.g., 1000–2000 counts instead of about 5000–10 000 counts per channel close to the foil. As described below this was found to affect the lifetimes obtained from the computer fits to a substantial degree. In the case of the $4p\ ^2P$ level in Zn II, the lifetime of which does not differ much from those of the pri-

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mary cascade levels, we also performed an analysis with the method of arbitrarily normalized direct cascades (ANDC) by Curtis et al. [11].

3. Results

Our spectra between 2000 and 5000 Å showed many Zn I and Zn II multiplets. In the Zn I singlet system transitions from e.g., $4p\ ^1P$, $5s\ ^1S$ and $5d\ ^1D$ levels were observed. The triplets were strongly populated and transitions between $4p\ ^3P$ and $ns\ ^3S$ ($n = 5$–7) and $md\ ^3D$ ($m = 4$–7) were rather prominent. In the Zn II doublet system levels up to $7s$, $7p$, $8d$ and $6f$ as well as a few $3d^9 4snl$ levels were excited in our source. It is worth noting that we also observed lines at 4297 and 4302 Å which were reported but left unclassified by Crooker and Dick [12]. Because of the emphasis on obtaining good lifetimes for low-lying states in Zn I and Zn II, no efforts were made to obtain more detailed wavelength spectra.

3.1. *Zn I lifetimes*

The lifetimes for the $4s4p\ ^1P$ and $4s4d\ ^3D$ levels in Zn I were directly measured whereas information about the $4s4d\ ^1D$ decay time was obtained from the decay curve of the $4s^2\ ^1S$–$4s4p\ ^1P$ resonance transition.

Figure 1 shows one of our decay curves for the $4s4p\ ^1P$ level. In this particular measurement the energy after the foil was 215 ± 4 keV. The data shown in Fig. 1 were accumulated during 40 min. The beam fluctuations were less than 5% during this measurement. Altogether 8 decay curves, at three different energies, were taken for the Zn I resonance line and from these we obtain a mean lifetime of $\tau = 1.33 \pm 0.07$ ns for the $4s4p\ ^1P$ level. This result is in Table I compared to previous experimental and theoretical values.

The phase-shift result of Baumann and Smith [13] is significantly longer than our new lifetime whereas we agree reasonably well with results based on level-crossing [14–16], beam-foil [17] and absorption [18] measurements.

The $4s^2\ ^1S$–$4s4p\ ^1P$ transition has also been theoretically studied by several authors. In the work of Warner [19] and Helliwell [20] configuration mixing was hardly considered and this should explain their high f-values and too short lifetimes. The semi-empirical calculations of Antena and Zilitis [21] resulted in a $4s4p\ ^1P$ lifetime which also seems to be too short by 15–20%. In a later work Zilitis [22] studied the f-value for the Zn I resonance line using a number of methods and approximations. The f-values so obtained range from 1.079 to 1.836. In Table I we only include one of the values which is reasonably close to experimental findings. The random-phase approximation (RPA) calculations of Amusiya et al. [23] take into account the correlations within the $n = 4$ shell as well as interactions of the valence electrons with the $3d^{10}$ core. The value so obtained is in good agreement with recent experiments (including this work) and the multiconfiguration Hartree–Fock (MCHF) treatment of Froese Fischer and Hansen [5] who also included correlations between $n = 4$ and $n = 3$ electrons. Finally there is a value by Chu and Johnson [24] based on frozen-core random-phase-approximation. This oscillator strength is somewhat higher than other recent theoretical values; this may be partly due to the neglect of core polarization effects. It is evident from Table I that for the Zn I resonance line there is excellent agreement between modern experimental and theoretical transition probabilities. There are obvious parallels to previous beam-foil studies of resonance lines for other neutral atoms with two valence electrons, e.g., Be [25], Mg [7] and Ca [26]. In all cases the decay curves are easily analyzed and the measured results practically coincide with those predicted by many-electron theories.

The $4s4p\ ^1P$–$4s4d\ ^1D$ transition, at 6362 Å, lies outside the wavelength range of our experiment. However, after the initial fast depopulation the decay of the $4s4p\ ^1P$ level is governed by the decay rate of the $4s4d\ ^1D$ term (Fig. 1) the lifetime of which may therefore be determined from the decay curve of the 2139 Å resonance transition. This claim is supported by previous work using electron excitation [27] or electron-photon coincidence [28] methods which show that the $4s4d\ ^1D$ lifetime is close to

TABLE I. *Radiative lifetimes in Zn I*

Transition	Wavelength (Å)	Lifetime of upper level (ns) This work	Other experiments	Theory
$4s^2\ ^1S$–$4s4p\ ^1P$	2139	1.33 ± 0.07	1.38 ± 0.05[b] 1.41 ± 0.04[c] 1.75 ± 0.2[d] 1.45 ± 0.15[e] 1.43 ± 0.15[f] 1.41 ± 0.04[g]	1.16[h] 1.06[i] 1.16[k] 1.45[l] 1.37[m] 1.38[n] 1.29[o]
$4s4p\ ^1P$–$4s4d\ ^1D$	6362	20.5 ± 1.5[a]	27.4[p] 23.2 ± 2.0[q] 21.1 ± 0.4[r]	13.5[k]
$4s4p\ ^3P$–$4s4d\ ^3D$	3345	5.4 ± 0.6	7.28[p] 8.8 ± 0.6[q] 6.7 ± 0.5[e]	3.49[k]

[a] Measured from cascades of the $4s^2$–$4s4p$ decay curves.
[b] Landman and Novick [14].
[c] Lurio et al. [15].
[d] Baumann and Smith [13].
[e] Anderson and Sørensen [17].
[f] Abjean and Johannin-Gilles [18].
[g] Kowalski and Träger [16].
[h] Helliwell [20].
[i] Warner [19].
[k] Antena and Zilitis [21].
[l] Zilitis [22].
[m] Amus'ya et al. [23].
[n] Froese Fischer and Hansen [5].
[o] Chu and Johnson [24].
[p] Schuttevaer and Smit [29].
[q] Osherovich et al. [27].
[r] Shaw et al. [28].

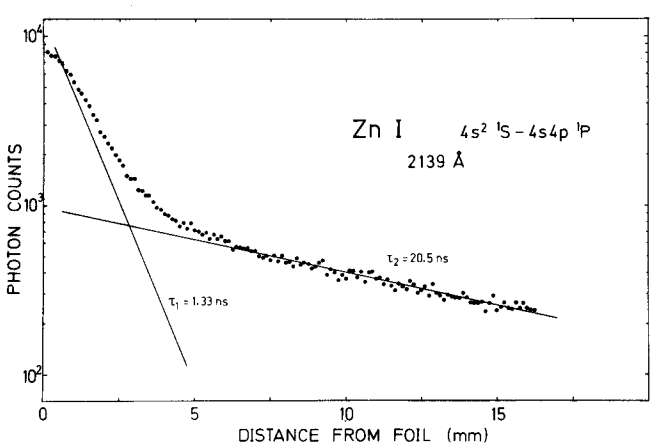

Fig. 1. Intensity decay of the 2139 Å line in Zn I ($4s^2\ ^1S$–$4s4p\ ^1P$). A decomposition of this decay curve yields the lifetime of the $4s4p\ ^1P$ term ($\tau_1 = 1.33$ ns) as well as of the $4s4d\ ^1D$ term ($\tau_2 = 20.5$ ns).

20 ns while other levels that directly feed the $4s4p\ ^1P$ term, e.g. $4s5s\ ^1S$ and $4s5d\ ^1D$, have substantially longer lifetimes. By computer-fitting our decay curve for the 2139 Å line to two exponentials we thus obtain a slower component of 20.5 ± 1.5 ns which is ascribed to the $4s4d\ ^1D$ term. This value is less accurate than that obtained by Shaw et al. [28] – the two-exponential fit in our case is clearly an oversimplification – but the agreement is still quite good. It is interesting to note that there is also a rather old value, based on emission measurements [29] which agrees surprisingly well with more recent data.

In the Zn I triplet system we only measured the $4s4d\ ^3D$ lifetime. The decay curves were decomposed into two exponentials yielding a lifetime of 5.3 ± 0.6 ns for the $4d\ ^3D$ term. This value does not agree with that found by Osherovich et al. [27], the agreement being better – but far from perfect – with the previous beam-foil result [17]. Our analyses showed that if the decay curves are fitted to one exponential and a constant background lifetimes very close to 6.5–7.0 ns are obtained. However, both the DISCRETE program and hand fits clearly favour a two-exponential approximation with a correspondingly shorter primary decay time. It should be noted that the lifetimes determined by Schuttevaer and Smit [29] exceed our values by about 35% both for the $4d\ ^1D$ and ^3D terms. Emission measurements usually give accurate relative lifetimes but there are difficulties with obtaining the absolute *f*-value scale. The relative intensities of [29] were later confirmed by Penkin and Red'ko [30] who used the hook method. For certain triplet multiplets our measured intensity ratios also agree with [29] and [30]. A theoretical study, similar to that described in [5] would clearly be quite interesting for the 4*p*–4*d* singlet and triplet transitions in Zn I.

3.2. *Zn II lifetimes*

In this spectrum we determined the lifetimes for the $4p\ ^2P$, $4d\ ^2D$, $5s\ ^2S$ and $5p\ ^2P$ terms. The 4*p* lifetime was only measured from the 2025 Å line ($4s\ ^2S_{1/2}$–$4p\ ^2P_{3/2}$). The other component ($4s\ ^2S_{1/2}$–$4p\ ^2P_{1/2}$) at 2062 Å could be partially resolved from the Zn II line at 2064 Å ($4p\ ^2P_{1/2}$–$4d\ ^2D_{3/2}$) when narrow slits were used but then the counting rate became too low for reliable lifetime measurements.

Because of the favourable intensity of the 2025 Å line when broad slits (200 μm) were used it was possible to obtain good statistics within a very short time. The lifetime of the $4p\ ^2P_{3/2}$ level was then determined by both exponential curve fitting and by a transient replenishment balance [11, 31], made jointly among the decay curves of the $4p\ ^2P_{3/2}$, $4d\ ^2D_{5/2}$ and $5s\ ^2S_{1/2}$ levels. The latter analysis utilizes linear relationships which connect the measured 4*p* decay curve, $I_{4p}(t)$, with those of its direct cascades, $I_{ns}(t)$ and $I_{nd}(t)$, from excited ns and nd levels. Here *t* is the time-of-flight of the ion beyond the foil, computed from the position and the ion velocity. If all the decay curves are determined under similar conditions and have a common initialization of time, they are related by the dynamic population equation for the 4*p* level, which can be written

$$-\mathrm{d}I_{4p}/\mathrm{d}t = \alpha_{4p}I_{4p}(t) - \xi_{4d}I_{4d}(t) - \xi_{5s}I_{5s}(t) - \xi_{5d}I_{5d}(t) - \ldots \quad (1)$$

Here $\alpha_{4p} \equiv 1/\tau_{4p}$ is the inverse of the lifetime of the 4*p* level and the ξ_{nl} factors are constants which renormalize the measured decay curves to their correct (relative) emitted intensities. If ξ_{nl} is not known, $I_{nl}(t)$ is called an "arbitrarily normalized decay curve" (ANDC), while if $\xi_{n'l'}$ is known, $I_{n'l'}(t)$ is called a "relatively normalized decay curve" (RNDC). In our analysis 4*d* was an ANDC, 5*s* was an RNDC, while 5*d* and all higher levels were neglected. In this case, eq. (1) can be rewritten

$$y(t) = \alpha_{4p} - \xi_{4d}x(t) \quad (2)$$

where

$$y(t) \equiv -\mathrm{d}(\ln I_{4p})/\mathrm{d}t \quad (3)$$

and

$$x(t) \equiv [I_{4d}(t) + bI_{5s}(t)]/I_{4p}(t) \quad (4)$$

The quantity $b \equiv \xi_{5s}/\xi_{4d}$ has been independently determined by Hultberg et al. [32] using an intensity-calibrated detection system for beam-foil measurements. To utilise eqs. (2–4), our measured decay curve data for the 4*p*, 4*d* and 5*s* levels in Zn II were subdivided into successive non-overlapping 7-point regions, and $y(t)$ and $x(t)$ were computed at the center of each region by numerical differentiation and averaging techniques (various other subdivision sizes were also tested, but the final results were insensitive to this choice). Statistical uncertainties from the decay curves were propagated to determine the statistical uncertainties in $y(t)$ and $x(t)$, and a weighted linear regression was performed to determine α_{4p} and ξ_{4d}. The results are shown in Fig. 2. Here the units of $x(t)$ were chosen so that $x(0) = 1$; in such a case ξ_{4d} has a simple relationship to the initial replenishment ratio $R(0)$ [31]. The *y* and *x* intercepts on this plot (Fig. 2), correspond to the reciprocals of the lifetime τ_{4p} and $R(0)$. We obtain the results $\tau_{4p} = 2.07$ ns and $R(0) = 0.34$. The analyses of Hultberg et al. [32] indicated an initial replenishment ratio of $R(0) = 0.49$ which broke down into 0.32 from 4*d*, 0.13 from 5*s*, 0.03 from 5*d* and less than 0.02 from the sum of contributions from the 6*s*, 7*s*, 8*s* and 6*d* levels. This indicates that nearly all of the cascading into the 4*p* level has been included in our analysis. The statistical uncertainties in this lifetime determination were 4% and the velocity determination was accurate to within 2% in this particular case. The uncertainty in the lifetime due to the neglect of cascades from levels higher than 5*s* is difficult to estimate but simulations indicate that it should not exceed 3%. We therefore estimate the total uncertainty of our $4p\ ^2P_{3/2}$ lifetime to be less than 10%.

In addition to this ANDC analysis we also decomposed the $4p\ ^2P_{3/2}$ decay curve into exponentials using the DISCRETE

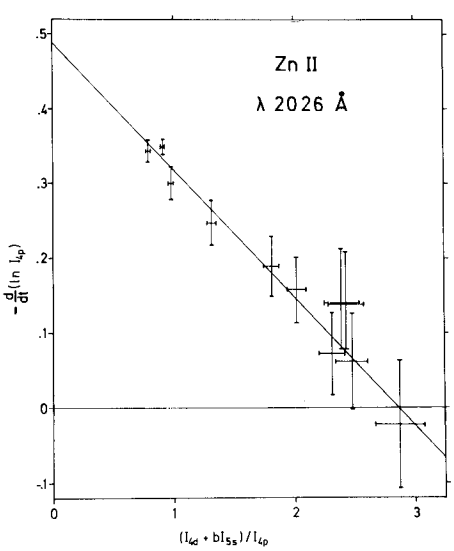

Fig. 2. Replenishment Plot of *y* versus *x* (as defined in Eqs. 3 and 4 with *b* obtained from ref. [32]), for the $4p\ ^2P_{3/2}$ level. The line is a least squares regression of the data to Eq. (2), weighted according to statistical uncertainties.

Table II. *Radiative lifetimes in Zn II*

Transition	Wavelength (Å)	Lifetime of upper level (ns) This work	Other experiments	Theory
$4s\ ^2S_{1/2}$–$4p\ ^2P_{3/2}$	2025	2.07 ± 0.20	3.1 ± 0.4[b] 3.0 ± 0.3[c] 3.0 ± 0.3[c] 2.4 ± 0.3[e] 3.2 ± 0.2[f]	1.81[g] 2.51[h] 2.04[i]
$4p\ ^2P_{3/2}$–$4d\ ^2D_{5/2}$	2099	1.40 ± 0.15	3.85 ± 0.7[b] 2.3 ± 0.2[c] 1.8 ± 0.4[d]	1.19[g] 1.29[i]
$4p\ ^2P_{1/2,3/2}$–$5s\ ^2S_{1/2}$	2501, 2557	1.8 ± 0.2	3.85 ± 0.7[b] 2.0 ± 0.2[c]	1.41[g] 2.48[i]
$5s\ ^2S_{1/2}$–$5p\ ^2P_{1/2,3/2}$	7732, 7588	17 ± 2[a]		15.49[i]

[a] Measured from cascades of the 4*p*–5*s* decay curves.
[b] Baumann and Smith [13].
[c] Andersen and Sørensen [17].
[d] Andersen et al. [33].
[e] Rambow and Schearer [34].
[f] Shaw et al. [28].
[g] McGinn [36].
[h] Froese Fischer [3].
[i] Lindgård and Nielsen [35].

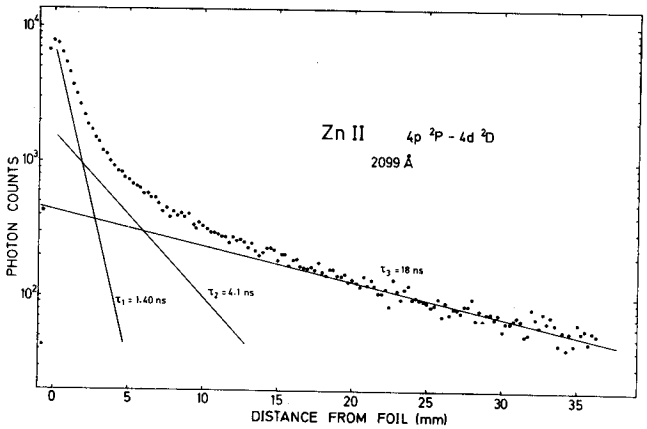

Fig. 3. Intensity decay of the 2099 Å line in Zn II ($4p\ ^2P_{3/2}$–$4d\ ^2D_{5/2}$). The decay curve is approximated to a sum of three exponentials of which $\tau_1 = 1.40$ ns is due to spontaneous decay of the 4*d* level. The longer-lived components, $\tau_2 = 4.1$ ns and $\tau_3 = 18$ ns are mainly due to cascading from the 4*f* and 5*p* levels, respectively.

program. A two-exponential fit was selected by the computer with a $4p\ ^2P$ lifetime of 2.48 ns, whereas the mean value of hand-fits was 2.52 ns. The longer-lived component, close to 15 ns, is ascribed to the $5p\ ^2P$ level (see below) which indirectly feeds $4p\ ^2P$. The $4p\ ^2P$ lifetime values close to 2.5 ns thus reflect the neglect of cascading from the short-lived $4d\ ^2D$ and $5s\ ^2S$ terms into $4p\ ^2P$. These effects are only taken care of by the ANDC analysis. Our result of 2.07 ns (Table I) is markedly shorter than the early beam-foil value of Anderson and Sørensen [17]. Later, Andersen et al. [33] investigated Zn II lifetimes using the fast-beam level-crossing method. Neither of these two – mutually consistent – results agrees well with our value. This is somewhat puzzling, partly because of the systematic study of experimental errors in [33]. However, as shown in Fig. 2, a lifetime close to 3 ns is totally ruled out in the ANDC representation. Nor do we agree with the result of Shaw et al. [28]. However, these authors had to use an instrumental time resolution of more than 4 ns which – together with very low counting rates in the Zn II case – could explain the discrepancy. As Table II further shows there is another short 4*p* lifetime value, by Rambow and Schearer [34], who performed level-crossing measurements. The agreement is good with our new value – it is worth adding that [34] also gives lifetimes in Mg I and Ca I which are in perfect agreement with previous beam-foil results [7, 26].

There are three theoretical values for the $4p\ ^2P_{3/2}$ level lifetimes (Table II). Our experiment agrees best with the Coulomb-approximation calculations of Lindgård and Nielsen [35]. The more sophisticated MCHF study of Froese Fischer [3] here predicts a lifetime which is about 20% longer than our experimental values.

Figure 3 shows one of the decay curves obtained for the 2099 Å line ($4p\ ^2P_{3/2}$–$4d\ ^2D_{5/2}$). This curve and several others were decomposed into three exponentials and – because of the good statistics – the decompositions were found to be unique. The primary component 1.40 ± 15 ns is in very good agreement with the calculations of McGinn [36] who used a pseudopotential method and of Lindgård and Nielsen [35]. We also confirm the short lifetime found by Anderson et al. [33] while the very short initial decay must have been overlooked in [13] and [17].

The other exponentials in Fig. 3, corresponding to 4.1 ± 0.6 and 18 ± 2 ns, agree with the theoretical values for the $4f\ ^2F$ and $5p\ ^2P$ terms, 4.81 and 15.49 ns respectively [35], which adds confidence to the three-exponential fit in this case.

For both the $4p\ ^2P_{3/2}$ and $4d\ ^2D_{5/2}$ levels we tested our methods of analysis by using individual runs of shorter accumulation time per channel, thus increasing the statistical uncertainties (as briefly mentioned in Section 2). Analysis of such "data" gave lifetimes close to 3 ns and 2.5 ns for the 4*p* and 4*d* levels, respectively. This example clearly illustrates the importance of minimizing the statistical uncertainties in complex beam foil decay curves.

The $5s\ ^2S_{1/2}$ lifetime was determined from both the 2501 Å and 2557 Å lines with practically identical results. Here our result 1.8 ± 0.2 ns is in good agreement with the previous beam-foil experiment [17]. These experimental values do not agree with that of the Coulomb approximation calculation [35] which indicates that there may be some theoretical problems for the $l = 0$ states.

An interesting by-product of these measurements is that we also obtain a reasonably accurate experimental value for the $5p\ ^2P$ term in Zn II, using the cascade method described above. All $5s\ ^2S$ decay curves showed a marked two-exponential shape, and the longer lifetime, 17 ± 2 ns, is ascribed to the $5p\ ^2P$ term. Here the theoretical values [35] are 15.49 ns ($5p\ ^2P_{3/2}$) and 17.06 ns ($5p\ ^2P_{1/2}$). Direct cascading into $5s\ ^2S$ is possible only from $np\ ^2P$ terms and those with $n \geqslant 6$ have all quite long lifetimes [35]. Here we have another example of the cascade-lifetime method by which lifetimes can be measured for levels not easily accessible for direct study. Of course, this method only works when the spectrum is simple, the cascade levels can be easily identified and there is approximate previous lifetime information.

4. Conclusion

A new beam-foil study of Zn I and Zn II lifetimes has been described. The lifetimes were extracted from high-quality decay curves, obtained under various experimental conditions. Curve-fits using a computer were found to give unique decompositions

whenever the primary and cascade lifetimes differ by a factor of five or more. The somewhat more complicated ANDC method was applied to the $4p\ ^2P$ level in Zn II for which the cascading is of a much more pronounced character.

Our beam-foil results confirm previous data for the $4s^2\ ^1S$–$4s4p\ ^1P$ resonance transition in Zn I. Agreement is also satisfactory with previous experiments for the $4s4p$–$4s4d$ singlet and triplet transitions. For these, as well as for other Zn I lines, new calculations seem to be desirable, however.

In Zn II our new lifetimes are somewhat shorter than previous experimental values. This is particularly evident in the case of the $4p\ ^2P$ level. Here we note a significant difference between our value and the majority of previous experimental results. The present study makes clear – not unexpectedly – that curve fitting and ANDC analysis (the latter of which takes care of cascading in a much more direct way) may yield significantly different primary lifetimes whenever the cascading situation is complicated. Indeed there are several previous studies, e.g., [37, 38]. which analyze cases when multi-exponential fits to decay curves yield 20–30% too long lifetimes. With this fact in mind the ANDC lifetime for the $4p\ ^2P$ level in Zn II must be preferred. In other Zn II cases the decay curves were easily analyzed and the various components were found to correspond to definite cascading level. Such a result strengthens the belief in curve-fitting data for the $5s\ ^2S$ and $4d\ ^2D$ decays. As a result of our Zn II studies the agreement between beam-foil lifetimes and those predicted by theoretical analysis has improved. Work is in progress to make similar studies for other members of the Cu I and Zn I isoelectronic sequences.

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