

LIFETIMES OF EXCITED STATES IN Mg I, Cd I, AND Mg II

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ABSTRACT

The beam-foil technique has been used to measure mean lives of some excited states in Mg I, Cd I, and Mg II. The reported Mg I and Cd I lifetimes are considerably shorter than the mean lives recently reported by Schaefer, using the delayed-coincidence technique.

I. INTRODUCTION

Several atomic lifetimes of excited states in neutral and singly ionized magnesium have been reported during the last few years. The consistency between the experimental lifetime data obtained by Smith and Gallagher (1966), using the Hanle effect; Andersen *et al.* (1970a) and Berry, Bromander, and Buchta (1970), using the beam-foil technique; and Smith and Liszt (1971), applying the phase-shift method, shows that these experimental methods may yield reliable oscillator strengths for transitions in Mg I and Mg II. This is of importance for the evaluation of the astrophysical abundance of magnesium.

The oscillator strengths derived so far from the published mean lives mainly concern transitions below 4000 Å. Difficulties in connection with the lack of detailed knowledge of the continuous absorption coefficient indicate that abundance analyses for magnesium should not be performed on spectral lines with $\lambda < 4000$ Å.

Recently Schaefer (1971a) reported a large number of mean lives for singlet and triplet terms in Mg I together with a few mean lives for Mg II. Several of the transitions used in his investigations (3^1P-n^1D , $n = 3-7$, 3^1P-m^1S , $m = 5-6$) are among the spectral lines selected by Lambert and Warner (1968) as being suitable for abundance determinations, taking into account that blending must not occur and that the strength of the Fraunhofer line must not exceed $\log W_\lambda/\lambda = -5.0$. Schaefer's (1971a) results were obtained by the delayed-coincidence technique and with an inverted hollow-diode as excitation source.

For the $3p^2P$, $4s^2S$, and $4f^2F$ levels in Mg II, the lifetimes reported by Schaefer (1971a) are 50-100 percent longer than those obtained by Andersen *et al.* (1970a) by beam-foil measurements, Smith and Liszt (1971) by the phase-shift technique, or the calculations by Warner (1968a) and Wiese, Smith, and Miles (1969). This discrepancy for the Mg II mean lives initiated a reinvestigation of atomic lifetimes in Mg I by using the beam-foil technique.

Applying the same experimental technique as for magnesium, Schaefer (1971b) has also reported a number of mean lives for excited states in neutral and ionized cadmium. In order to clarify the lack of consistency discussed above, atomic mean lives of some selected levels in Cd I were measured by the beam-foil technique.

II. EXPERIMENTAL METHOD

The experimental procedure for beam-foil studies of magnesium has been reported by Andersen *et al.* (1970a), and the same technique was applied for the investigation of cadmium. Cadmium-ion beams were obtained from cadmium pellets placed in a heated crucible from which cadmium evaporated into the ion source.

Schaefer (1971*a*) has reported mean lives of seventeen Mg I levels, five of which belonged to triplet terms and twelve to singlet terms. Foil excitation of 50–500-keV Mg⁺ beams mainly leads to population of triplet terms. In the present case, only the transitions 3^3P-4^3S , 3^3P-3^3D , 3^3P-4^3D , and 3^1P-4^1D were sufficiently strong to allow a lifetime determination with the beam-foil technique.

In the case of Cd I, Schaefer (1971*b*) reported the mean lives of five triplet terms and seven singlet terms. Only the triplet terms were populated sufficiently by the foil-excitation technique for cadmium-ion beams within the energy range 200–500 keV to allow accurate lifetime measurements.

Cascade corrections are important in beam-foil studies. An extensive variation of the initial ion energy has been used to facilitate such corrections. Scattering and energy loss in the carbon foil are other sources of error. For magnesium, the energy loss in $5\text{-}\mu\text{g cm}^{-2}$ carbon foils was calculated to be 16 keV at 300 keV and 20 keV at 500 keV, using the formulae of Lindhard, Scharff, and Schiøtt (1963). At lower energies, the energy loss was determined by an electrostatic analysis of the beam after its passage through the carbon foil. The same technique was used to determine the energy loss of the cadmium beam. At 300 keV, the experimental energy loss was 35 keV for a cadmium beam, approximately 60 percent of the total energy loss due to electronic as well as nuclear stopping processes. It seems to be a general trend in beam-foil studies that only a fraction of the theoretically estimated energy loss should be included. In a beam-foil experiment, the particles moving in the forward direction are characterized by small energy loss and high excitation cross-sections, in contrast to the particles that have experienced wide-angle scattering and large energy loss due to nuclear stopping, and these latter particles have low excitation cross-sections.

Thus only a minor fraction of the nuclear stopping should be included when the energy loss is evaluated. This is of importance not only for heavy atoms but also for light atoms at low energies. Hvelplund *et al.* (1970) have described this correction and have also shown that the energy spread for ion beams emerging from thin carbon foils in the forward direction is limited. For a 300-keV cadmium beam, the full width at half-maximum in the energy distribution will be ~ 15 keV.

Scattering in the carbon foils causes line-broadening, and for lifetimes longer than ~ 25 nanoseconds (ns), the scattering may cause a minor shortening of the observed lifetime.

The accuracy in the mean-life determinations depends on several factors and can vary according to spectral intensity, energy loss in the foil, possible line mixing, cascade corrections, and scattering. The distance from the carbon foil to the optical axes of the monochromator can be determined with an accuracy of approximately 2 percent, the ion velocity to within 2 percent. For exponential decay curves containing more than one component, the resolution of the decay curves was performed with an accuracy of the order of 4–5 percent. This correction depends on the ratio of the mean lives of the decaying components as well as on their initial intensity values. Only decay curves obtained with perfect foils were accepted. Spectral intensity tests were performed for each decay curve to ensure that the carbon foil had remained unbroken and yielded the same excitation of the beam before and after a decay curve had been recorded. The quoted results are the average values of from three to 10 measurements. The highest accuracy obtained for the average value of 10 determinations in the present investigations is considered to be ~ 5 percent.

III. RESULTS

Table 1 shows the Mg I lifetime data. The mean lives reported by some of the authors (1970) for $3s3d^3D$ and $3s4d^3D$ levels were confirmed within the experimental error.

TABLE 1
LIFETIMES MEASURED OR CALCULATED IN Mg I

Wavelength (Å) (1)	Transition (2)	τ (ns) (3)	τ (ns) (4)	τ (ns) (5)	τ (ns) (6)	τ (ns) (7)
5183 5172 5167	3^3P-4^3S	13 ± 1	10.1 ± 0.8	14.8 ± 0.7	12.8	9.6
5528	3^1P-4^1D	...	32 ± 3	54.9 ± 1.4	31.6	...
3835	3^3P-3^3D	3.7 ± 1	6.6 ± 0.5	11.3 ± 0.8	6.1	6.0
3095	3^3P-4^3D	10 ± 1	13.5 ± 1.0	18.4 ± 0.7	15.1	...

NOTE.—Columns (1) and (2) specify the wavelength and transition of interest; column (3), lifetimes reported by Berry *et al.* (1970); column (4), the result of this work, column (5), lifetimes reported by Schaefer (1971a); column (6), lifetimes from Warner (1968a, b); and column (7), lifetimes calculated from Weiss (1967).

The 5528 Å 3^1P-4^1D transition exhibited a purely exponential decay over nearly two decades and no indication of a cascading component, whereas the 4^3S lifetime was obtained after correcting for a long-lived cascading component (~ 50 – 60 ns), accounting for 15 percent of the photons emitted immediately after the foil.

Atomic mean lives for Cd I obtained with the beam-foil technique are given in table 2 together with results obtained by Laniece (1968, 1970), using the Hanle-effect method, Verolainen and Osherovich (1966), using electron-beam excitation with delayed-coincidence technique, and Schaefer's results (1971b).

The 7^3S , 5^3D , 6^3D , and 7^3D lifetime data were corrected for weak cascading components. The cascade-corrected lifetime was 10–15 percent shorter than the lifetime obtained without corrections. Since the decay of all spectral lines involved could be followed over a distance long enough to yield an accurate determination of the cascade component, a proper correction could be performed in all cases. In the 6^3S case, the cascade component was more dominant. For the 4800 Å and 5086 Å spectral lines, it accounted for 20–25 percent of the photons emitted immediately after the foil. Since the lifetime of the cascading component was ~ 50 ns, it was possible to perform the cascade correction with good accuracy.

A few Mg II mean lives given in table 3 were derived from purely exponential decay curves over 1.5–2 decades or after subtraction of a very weak long-lived component. The cascade-corrected values deviate less than 5 percent from the uncorrected values.

TABLE 2
LIFETIMES MEASURED IN Cd I

Wavelength (Å) (1)	Transition (2)	τ (ns) (3)	τ (ns) (4)	τ (ns) (5)	τ (ns) (6)
4800, 5086	5^3P-6^3S	8.9 ± 1.0	18.5 ± 2.0	9.2 ± 0.3	10.6 ± 0.8
3081, 3133	5^3P-7^3S	13.7 ± 1.5	29.9 ± 4.5	...	...
3612	$5^3P_2-5^3D_3$	6.7 ± 0.5	14.7 ± 2.2	7.0 ± 0.4	14.5 ± 1.5
3466	$5^3P_1-5^3D_2$	6.4 ± 0.5		6.8 ± 0.4	
3404	$5^3P_0-5^3D_1$	6.4 ± 0.5		6.7 ± 0.4	
2881	5^3P-6^3D	11.5 ± 1.0	18.7 ± 2.4	...	...

NOTE.—Columns (1) and (2) specify the wavelengths and transitions of interest; column (3), the result of this work; column (4), lifetimes reported by Schaefer (1971b); column (5), lifetimes reported by Laniece (1968, 1970), using Hanle effect measurements; and column (6), lifetimes reported by Verolainen and Osherovich (1966) using delayed-coincidence technique.

TABLE 3
LIFETIMES MEASURED IN Mg II

Wavelength (Å) (1)	Transition (2)	τ (ns) (3)
7896, 7877.....	4^2P-4^2D	12.2 ± 0.7
2660.....	3^2D-6^2F	11.7 ± 0.8
6346.....	4^2D-6^2F	
5264.....	4^2D-7^2F	
		21 ± 3

NOTE.—Columns (1) and (2) specify the wavelengths and transitions of interest; column (3), the result of this work.

IV. DISCUSSION

The present Mg I and Cd I mean lives determined by the beam-foil technique are considerably shorter than the values obtained by Schaefer (1971*a, b*), using delayed-coincidence technique. The discrepancies range from 40 percent to 100 percent, the same order of discrepancy as that observed for the levels in Mg II.

The mean lives for the $3s4s^3S$, $3s3d^3D$, and $3s4d^3D$ levels in Mg I have been studied by Berry *et al.* (1970), who also used the beam-foil technique. Their 13 ± 1 ns mean life for the $3s4s^3S$ level is in rather good agreement with the result reported by Schaefer (1971*a*), but no correction for cascading was performed. In the present study, the decay curve was followed over a distance 100 mm long, and a long-lived cascade component (~ 50 – 60 ns), accounting for 15 percent of the photons emitted immediately after the foil, was observed. If only the initial part of the decay curve was used to determine the mean life, no cascade component could be observed, and a mean life of ~ 14 – 15 ns would be obtained.

For the $3s3d^3D$ level, the 3.7 ± 1.0 ns value reported by Berry *et al.* (1970) is probably incorrect. They reported the presence of a growing-in cascade following the decay of the 3835 Å spectral line, which indicated an uncertainty concerning the identification of the 3835 Å line in their study as only representing the $3s3p^3P-3s3d^3D$ transition. No growing-in cascade was observed in this study, which supports the hypothesis of line-blending in the study by Berry *et al.* (1970).

The difference between the two beam-foil values for the $3s4d^3D$ level is not due to cascade corrections since the decay curve is well represented by a single exponential function. However, since the measurements by Berry *et al.* (1970) were performed at lower energies than those used in the present study, scattering of particles was much more dominant; this may account for the discrepancy.

The $3s4d^1D$ level in Mg I has previously been studied by Karstensen and Schramm (1968), who reported a 59 ± 5 ns lifetime from an atomic-beam measurement. As they pointed out, the cascading components populating the 4^1D level (4^1F , 5^1F , and 5^1P) probably all have mean lives ranging from 50 to 90 ns, which may influence their results and also those of Schaefer (1971*a*). Contrary to the beam-foil source operated under the present conditions, their excitation technique populates many and high-lying singlet levels in neutral magnesium. The present beam-foil data for Mg I are in agreement with theoretical mean lives derived from Weiss's (1967) and Warner's (1968*a, b*) *f*-value calculations.

For Cd I, the 6^3S lifetime determined by Lanier (1968), using the Hanle-effect technique, and the present value agree well. The result reported by Verolainen and Osherovich (1966), 10.6 ± 0.8 ns, and the value given by Hanle, Pepperl, and Reuscher (1969), 7 ± 1 ns, deviate only slightly from the present value. However, the $18.5 \pm$

2.0 ns mean life reported by Schaefer (1971*b*) is considerably longer than any of those four independent measurements.

The Hanle-effect measurements by Laniepce (1970) of the mean lives for the 5^3D levels agree well with the present values. In this case, also Schaefer's (1971*b*) value, 14.7 ± 2.2 ns, and the value of Verolainen and Osherovich (1966), 14.5 ± 1.5 ns, agree. However, there are certain indications that Verolainen and Osherovich's result may be erroneous. Systematic studies of atomic lifetimes and oscillator strengths in homologous neutral and singly charged gallium, indium, and thallium atoms by Andersen and Sørensen (1972) have shown that identical f -values are found for homologous transitions in these atoms. Preliminary studies of homologous transitions in neutral zinc, cadmium, and mercury atoms by Andersen, Jessen, and Sørensen (1970*b*) have indicated that the mean lives for the 4^3D_3 level in Zn I, 5^3D_3 in Cd I, and 6^3D_3 in Hg I ranged from 7 to 9 ns. New beam-foil-technique measurements using electrostatic analyses to determine the beam velocity after the passage through the carbon foil have yielded the values 4^3D_3 in Zn I, 6.8 ± 0.5 ns; 5^3D_3 in Cd I, 6.7 ± 0.5 ns; and 6^3D_3 in Hg I, 7.5 ± 0.6 ns. These atomic lifetimes will lead to identical f -values for the homologous m^3P_2 - m^3D_3 transitions in neutral zinc, cadmium, and mercury. A similar trend has been observed for other homologous transitions in these elements and will be published separately.

Verolainen and Osherovich (1966) have measured the 6^3D_3 mean life in Hg to be 8 ± 0.6 ns, in agreement with the beam-foil value. The lifetime recently reported by Osherovich *et al.* (1971) for the 4^3D_3 level in Zn I, 8.5 ± 0.6 ns, is slightly longer than the beam-foil value of 6.8 ± 0.5 ns, but is still in agreement with the systematic behavior of lifetimes of homologous levels in Zn I, Cd I, and Hg I. In this connection, the 14.5 ± 1.5 ns lifetime reported by Verolainen and Osherovich (1966) for the 5^3D_3 level in Cd I seems to be too long and may be in error.

The 7896 Å and 7877 Å spectral lines in Mg II are among the Fraunhofer lines selected by Lambert and Warner (1968) for the determination of the abundance of magnesium in the solar photosphere. The experimental lifetime is in good agreement with the theoretical value (12.6 ns) obtained from Coulomb approximations. The oscillator strengths for the $4p^2P$ - $4d^2D$ transitions derived from the present lifetime value for $4d^2D$ support a magnesium abundance to be $\log N(\text{Mg}) = 7.6$ on the scale where $\log N(\text{H}) = 12.00$. This magnesium abundance agrees with recent astrophysical considerations by Unsöld (1971).

For all investigated levels in Mg II, Mg I, and Cd I, the beam-foil data are in good agreement with data from other experimental methods, but they deviate considerably from the data obtained by Schaefer (1971*a, b*). The present investigations indicate that a systematic error is present in a number of the mean lives obtained with the delayed-coincidence technique based upon the inverted-hollow diode.

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