Systematic Study of Atomic Lifetimes in Gallium, Indium, and Thallium Measured by the Beam-Foil Technique

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Systematic studies of atomic lifetimes and oscillator strengths in the homologous atoms Ga, In, Tl and Ga^+, In^+, Tl^+ have been performed by measuring mean lives of excited atomic states using the beam-foil technique. The lifetimes of the lowest S levels in the neutral atoms, 6.9 ± 0.5, 7.5 ± 0.7, and 7.7 ± 0.5 nsec, respectively, for Ga, In, and Tl, are in agreement with recent reported values obtained by Hanle-effect and phase-shift techniques. Identical f values are found for homologous transitions in Al, Ga, In, and Tl, when configuration mixing can be excluded. The experimental results are compared with theoretical data based upon a single-configuration Coulomb approximation for neutral atoms and with a modified self-consistent-field approach for singly ionized atoms.

I. INTRODUCTION

The vapor-density independent methods for measuring atomic transition probabilities, such as level-crossing, phase-shift, and beam-foil techniques, have increased the reliability of the experimental results.

In the third group of the Periodic Table, a large number of experimental transition probabilities exist, particularly for the resonance transition in the neutral atoms. But it was not until recently, when Norton and Gallagher[1] reported the lifetimes for the $5\,^2S_{1/2}$ in Ga I, $6\,^2S_{1/2}$ in In I, and $7\,^2S_{1/2}$ in Tl I, that absolute transition probabilities could be established with reasonable accuracy.

In a previous paper,[2] it was shown that the beam-foil technique could yield lifetimes of resonance transitions in neutral gallium, indium, or thallium in agreement with results obtained by other techniques, but because of a large contribution of cascading from higher-lying levels, the beam-foil technique is less accurate for these levels as compared to higher-lying levels and levels in ionized species.

In contrast to other experimental methods, the beam-foil technique is not limited to the study of neutral atoms, but several excited levels in neutrals as well as ionized species become populated when heavy-ion beams are excited by carbon foils. Thus it is possible to study the systematic behavior of atomic lifetimes in a homologous sequence as for instance aluminum, gallium, indium, and thallium with this technique.

From a theoretical point of view, gallium, indium, and thallium is a sequence of interest since the singly ionized spectra of these elements originate from atoms with two electrons outside a closed shell of electrons. An extension of the Bates-Damgård approach (BD), which is valid in the single-electron case, has been applied by Helliwell[3] for the two-electron case. This approach, which has been named "the nodal-boundary-condition method" (NBCM), presents an alternative to the BD technique, successfully used in a number of cases.

II. EXPERIMENTAL TECHNIQUE

The 600-kV heavy-ion accelerator at University of Aarhus was used to accelerate ion beams of gallium, indium, and thallium. Usually, ion currents of tenths of microamperes were passed through 5-$\mu g/cm^2$ 2.5-mm diam carbon foils (Yissum Research Co., Israel). Ion beams of gallium were obtained by a conversion of gallium oxide into gallium chloride by means of the carbon tetrachloride method.[4] Indium and thallium pellets were placed in heated crucibles and evaporated into the ion source volume. The emission spectra downstream the excited foil were scanned with a 0.3-m model No. 218 McPherson monochromator.

As pointed out previously,[5] cascading corrections could be serious, especially for the resonance transitions. An extensive variation of the initial ion energy facilitates these corrections, and therefore doubly as well as singly charged ions were accelerated. Energy loss and scattering in the carbon foil are other sources of error. In Table I, the energy loss estimated from the Lindhard-Scharff-Schiøtt theory[6] is shown for 300- and 800-keV ions of gallium, indium, and thallium. The tabulated values are the total energy loss due to

TABLE I. Energy losses estimated from the Lindhard-Scharff-Schiøtt theory (Ref. 6).

	Energy loss (keV)		
Energy	Ga	In	Tl
300	40	65	95
800	35	60	115

TABLE II. Atomic lifetimes of gallium. Other lifetime measurements (nsec) in Ga I are $5\,^2S_{1/2}$ 6.8 ± 0.3 (Ref. 1), 7.6 ± 0.4 (Ref. 8), 9.9 ± 0.2 (Ref. 9); $4\,^2D$ 7.7 ± 0.3 (Ref. 8).

Spectrum	Lower state	Upper state	Wavelength (Å)	τ (nsec)
Ga I	$4\,^2P_{3/2}$	$5\,^2S_{1/2}$	4172	6.9 ± 0.5
	$4\,^2P_{1/2}$	$5\,^2S_{1/2}$	4033	
	$4\,^2P_{3/2}$	$4\,^2D_{5/2}$	2944	6.4 ± 0.5
	$4P_{1/2}$	$4\,^2D_{3/2}$	2874	
	$4\,^2P_{3/2}$	$5\,^2D_{5/2}$	2500	14.0 ± 1.5
Ga II	$4\,^1P_1$	$5\,^1S_0$	2780	6.3 ± 0.8
	$4\,^1P_1$	$4\,^1D_2$	2700	15.8 ± 1.0
	$4\,^1D_2$	$4\,^1F_3$	3375	4.6 ± 0.6
	$4\,^3D_3$	$4\,^3F_4$	4262	6.0 ± 0.5
	$4\,^3D_{2,3}$	$5\,^3F_4$	2973	9.3 ± 1.0
	$4\,^3D_3$	$6\,^3F_4$	2555	11.5 ± 1.5
	$5\,^3P_2$	$6\,^3D_3$	3470	4.0 ± 0.6
Ga III	$4\,^2D$	$4\,^2F$	2424	1.7 ± 0.4
	$4\,^2F$	$5\,^2G$	4385	5.1 ± 0.7

electronic as well as nuclear stopping processes. In a beam-foil experiment, only particles leaving the foil within a certain small angle in the forward direction are observed. Therefore only a fraction of the nuclear stopping should be included when the energy loss is evaluated. This correction, described by Hvelplund *et al.*,[7] is only important in the present case for thallium. The reduced energy loss for a 300- and a 800-keV thallium ion beam amounts to 70 and 100 keV, respectively.

Scattering in the carbon foils causes line broadening, and for lifetimes larger than ≃ 25 nsec, the scattering may cause the observed lifetime to appear shorter.

III. EXPERIMENTAL RESULTS

Neutral atoms belonging to the third group of the Periodic Table are characterized by two series of spectral lines, $^2P_{1/2,3/2}$-$^2S_{1/2}$ (sharp series) and $^2P_{1/2,3/2}$-$^2D_{3/2,5/2}$ (diffuse series). The singly ionized spectra exhibit singlet or triplet transitions.

A. Gallium

The measured mean lives for excited levels in Ga I, Ga II, and Ga III are shown in Table II. For the $5\,^2S_{1/2}$ level, the value of 6.9 ± 0.5 nsec agrees well with the values of Cunningham and Link[8] (7.6 ± 0.4 nsec) and Norton and Gallagher[1] (6.8 ± 0.3 nsec), whereas the value of Demtröder[9] seems too high (9.9 ± 0.2 nsec). For the $4\,^2D_{3/2,5/2}$ levels, the value (6.4 ± 0.5 nsec) is lower than the 7.7 ± 0.3 nsec obtained by Cunningham and Link,[8] who measured the lifetime as an equally weighted average of the $^2D_{3/2}$ and $^2D_{5/2}$ states. The possibility of exciting higher-lying levels in the phase-shift method such as the $6\,^2S_{1/2}$ level, would result in a systematically too long mean life. Therefore, the phase-shift as well as the beam-foil technique shows a tendency towards too long mean lives if the necessary corrections, viz., excitation of other levels and cascading, respectively, have not been properly performed. The present data have all been corrected for cascade effects.

B. Indium

Only emission lines belonging to In I and In II were studied. The observed mean lives are listed in Table III. The $5\,^2D_{5/2}$ state shows a significantly longer mean life than does the $5\,^2D_{3/2}$ state. The present value for the $6\,^2S_{1/2}$ (7.5 ± 0.7 nsec) is in excellent agreement with the phase-shift measurement of Cunningham and Link[8] (7.5 ± 0.3 nsec), and a satisfactory agreement is also established between the $5\,^2D_{3/2,5/2}$ values. Norton and Gallagher[1] measured the lifetime of the $6\,^2S_{1/2}$ level to be 7.0 ± 0.3 nsec, which is very close to our value, but with larger uncertainties, viz., 7.5 ± 0.7 nsec. Hulpke *et al.*,[10] who used the same technique as Demtröder,[9] obtained a value of 8.53 ± 0.09 nsec for the lifetime of the $6\,^2S_{1/2}$ level, which seems inconsistent with the other results. Lifetimes of various singlet and triplet levels in In II have been measured and the values are listed in Table III. The intercombination line $5\,^1S$-$5\,^3P$ was measured and yielded a mean life of 125 ± 25 nsec for the $5\,^3P$ level in In II.

C. Thallium

Since thallium is a heavy element, energy loss and scattering in the foil might introduce large systematic errors. A comparison of the present results (Table IV) shows for the lifetime of the $7\,^2S_{1/2}$ state a remarkable agreement between the present value (7.7 ± 0.5 nsec) and the values obtained by Norton and Gallagher[1] (7.45 ± 0.2 nsec),

TABLE III. Atomic lifetimes of indium. Other lifetime measurements (nsec) in In I are $6\,^2S_{1/2}$ 7.5 ± 0.3 (Ref. 8), 7.0 ± 0.3 (Ref. 1), and 8.53 ± 0.09 (Ref. 10); $5\,^2D$ 7.9 ± 0.5 (Ref. 8).

Spectrum	Lower state	Upper state	Wavelength (Å)	τ (nsec)
In I	$5\,^2P_{3/2}$	$6\,^2S_{1/2}$	4512	7.5 ± 0.7
	$5\,^2P_{1/2}$	$6\,^2S_{1/2}$	4102	
	$5\,^2P_{1/2}$	$5\,^2D_{3/2}$	3039	6.3 ± 0.5
	$5\,^2P_{3/2}$	$5\,^2D_{5/2}$	3256	7.6 ± 0.5
	$5\,^2P_{1/2}$	$6\,^2D_{3/2}$	2560	21 ± 3
	$5\,^2P_{3/2}$	$6\,^2D_{5/2,3/2}$	2710, 2713	22 ± 3
	$5\,^2P_{3/2}$	$7\,^2D_{5/2,3/2}$	2522	50 ± 5
	$4P_{5/2}$	$5s\,5p\,6s\,^4P$	3187	5.4 ± 0.5
In II	$5\,^1P_1$	$6\,^1S_0$	2941	7.0 ± 1.0
	$5\,^1P_1$	$(5p)^2\,^1D_2$	2890	33 ± 5
	$(5p)^2\,^1D_2$	$4\,^1F_3$	3835	4.3 ± 0.5
	$5\,^3D_{2,3}$	$4\,^3F_3$	4652, 4685	7.3 ± 1.0
	$5\,^3D_2$	$5\,^3F_3$	3146	21 ± 2
	$5\,^3D_3$	$5\,^3F_4$	3158	21 ± 2
	$6\,^3P_1$	$7\,^3D_1$	3718	11.0 ± 2.0
	$5\,^3D_2$	$7\,^3P_1$	4028	4.5 ± 1.0
	$5\,^1S_0$	$5\,^3P_1$	2306	125 ± 25

TABLE IV. Atomic lifetimes of thallium. Other lifetime measurements (nsec) in Tl I are $7\,^2S_{1/2}$ 7.45 ± 0.2 (Ref. 1), 7.65 ± 0.2 (Ref. 8), 8.7 ± 0.3 (Ref. 9), 7.4 ± 0.3 (Ref. 11), and 7.6 ± 0.2 (Ref. 11); $6\,^2D$ 6.9 ± 0.4 (Ref. 8) and 6.2 ± 1 (Ref. 11).

Spectrum	Lower state	Upper state	Wavelength (Å)	τ (nsec)
Tl I	$6\,^2P_{3/2}$	$7\,^2S_{1/2}$	5350	7.7 ± 0.5
	$6\,^2P_{1/2}$	$7\,^2S_{1/2}$	3776	
	$6\,^2P_{3/2}$	$8\,^2S_{1/2}$	3229	23 ± 4
	$6\,^2P_{1/2}$	$8\,^2S_{1/2}$	2580	
	$6\,^2P_{3/2}$	$6\,^2D_{5/2}$	3519	7.6 ± 0.5
	$6\,^2P_{1/2}$	$6\,^2D_{3/2}$	2767	6.8 ± 0.5
	$6\,^2P_{3/2}$	$7\,^2D_{5/2}$	2918	19 ± 4
	$6\,^2P_{1/2}$	$7\,^2D_{3/2}$	2380	16 ± 4
	$6\,^2P_{3/2}$	$8\,^2D_{5/2}$	2709	50 ± 10
Tl II	$6\,^1P_1$	$7\,^1S_0$	3092	4.6 ± 0.5
	$6\,^1P_1$	$6\,^1D_2$	2531	5.0 ± 1.0
	$6\,^1D_2$	$5\,^1F_3$	4737	6.8 ± 0.8
	$6\,^3P_2$	$7\,^3S_1$	2298	18 ± 4
	$6\,^3D_2$	$5\,^3F_3$	5078	7.8 ± 1.0
	$6\,^3D_3$	$6\,^3F_4$	3369	9.3 ± 1.5

Cunningham and Link[8] (7.65 ± 0.2 nsec), and Gallagher and Lurio[11] (7.4 ± 0.3 and 7.6 ± 0.2 nsec). This result shows that with a reasonable accuracy, the foil-excitation technique can be applied to heavy-ion beams. Also for the $6\,^2D_{3/2}$ state, a reasonable agreement is found between the present data and earlier lifetime experiments.[6,9] For relatively long mean lives, the uncertainty caused by foil-scattering results in too short mean lives. This is especially the case for low primary-ion energies, and therefore more weight has been attached to the values obtained for 800-keV-ion beams.

IV. EVALUATION OF OSCILLATOR STRENGTHS

The experimental data presented in Sec. III were compared with earlier lifetime measurements only. For a large number of transitions in Al I, Ga I, In I, and Tl I, oscillator strengths have been measured by the method of the "hooks." Penkin and Shabanova[12–14] have measured relative oscillator strengths for both $n\,^2P_{1/2,3/2}$-$m\,^2S_{1/2}$ and $n\,^2P_{1/2,3/2}$-$m\,^2D_{3/2,5/2}$ transitions in Al I, Ga I, In I, and Tl I. From the present data, f values have been evaluated for the $n\,^2P_{1/2,3/2}$-$m\,^2S_{1/2}$ transitions in Ga I, In I, and Tl I, as shown in Table V. Included are earlier f values[15] in Al I and values obtained experimentally by Penkin and Shabanova[12–14] and theoretically by Gruzdev.[16] When f values are evaluated from lifetimes, the branching ratios have to be taken into account. In the case of Ga I and In I, pure L-S coupling was assumed, and no corrections for the different wavelengths of the two doublet transitions were performed. In Tl I, the wavelength of the two doublet transitions are 5350 and 3775 Å, respectively, which necessitates a proper correction. Further, L-S coupling can no longer be valid for Tl I.

The conversion of the lifetimes τ to the Einstein coefficients A was performed following the equation

$$1/\tau(7\,^2S_{1/2}) = A(7\,^2S_{1/2}\text{-}6\,^2P_{1/2}) + A(7\,^2S_{1/2}\text{-}6\,^2P_{3/2}) .$$

For the ratio

$$A(7\,^2S_{1/2}\text{-}6\,^2P_{3/2})/A(7\,^2S_{1/2}\text{-}6\,^2P_{1/2}) ,$$

the value of 1.13 ± 0.05 adapted by Gallagher and Lurio[11] has been used. This value is based on several relative intensity measurements.

Based on the lifetimes reported above, f values were calculated for $n\,^2P_{1/2,3/2}$-$m\,^2D_{3/2,5/2}$ transitions measured. Table VI shows the f values obtained together with f values in Al I based upon lifetimes previously reported.[15] To evaluate f values for a np-md transition from a lifetime measurement of the md level, it is necessary to have information about the branching ratio np-md/mp-md.

For Al I, Weiss[17] has calculated $A(4p\,^2P\text{-}4d^2D)$ to be 1.0×10^7 sec^{-1}. The lifetime for the $4d\,^2D$ level is determined to be 16.1 nsec[15] yielding a value of 5.2×10^7 sec^{-1} for $A(3p\,^2P\text{-}4d\,^2D)$. A similar calculation for the ratio

$$A(6p\,^2P\text{-}7d\,^2D)/A(7p\,^2P\text{-}7d\,^2D)$$

in Tl I shows a ratio of ~5, too. The Tl I calculation was based upon data in the paper by Gallagher and Lurio[11] and the present lifetimes for the $7d\,^2D$ and $6d\,^2D$ levels. The f values for Ga I and In I are calculated assuming a factor of 5 for the ratio

$$A(np\,^2P\text{-}md\,^2D)/A(mp\,^2P\text{-}md\,^2D) .$$

The uncertainty of the reported f values is probably less than 20%.

V. DISCUSSION

It has been the purpose of the present investigations to search for regularities in homologous sequences.

The f values calculated for the sharp series (Table V) show a good agreement with earlier experimental results obtained by the anomolous dis-

TABLE V. f values for $n\,^2P_{1/2,3/2}$-$m\,^2S_{1/2}$ transitions.

	Transitions	f value (this work)	f value[a] (expt)	f value[b] (theor)
Al I	$3\,^2P_{3/2}$-$4\,^2S_{1/2}$	0.12	0.15	0.11
	$3\,^2P_{1/2}$-$4\,^2S_{1/2}$	0.13	0.15	0.11
Ga I	$4\,^2P_{3/2}$-$5\,^2S_{1/2}$	0.13	0.13	0.13
	$4\,^2P_{1/2}$-$5\,^2S_{1/2}$	0.12	0.13	0.13
In I	$5\,^2P_{3/2}$-$6\,^2S_{1/2}$	0.15	0.14	0.12
	$5\,^2P_{1/2}$-$6\,^2S_{1/2}$	0.12	0.14	0.12
Tl I	$6\,^2P_{3/2}$-$7\,^2S_{1/2}$	0.14	0.13	0.13
	$6\,^2P_{1/2}$-$7\,^2S_{1/2}$	0.13	0.13	0.13

[a]References 12–14. [b]Reference 16.

TABLE VI. f values for $n\,^2P_{1/2,3/2}$-$m\,^2D_{3/2,5/2}$ transitions.

	Diffuse series					
	Transition	f value (this work)	Transition	f value (this work)	Transition	f value (this work)
Al I[a]	$3\,^2P_{3/2}$-$3\,^2D_{5/2}$	0.18	$3\,^2P_{3/2}$-$4\,^2D_{5/2}$	0.08		
	...	...	...	...		
Ga I	$4\,^2P_{3/2}$-$4\,^2D_{5/2}$	0.34	$4\,^2P_{3/2}$-$5\,^2D_{5/2}$	0.08		
	$4\,^2P_{1/2}$-$4\,^2D_{3/2}$	0.30	...	...		
In I	$5\,^2P_{3/2}$-$5\,^2D_{5/2}$	0.31	$5\,^2P_{3/2}$-$6\,^2D_{5/2}$	0.07		
	$5\,^2P_{1/2}$-$5\,^2D_{3/2}$	0.44	$5\,^2P_{1/2}$-$6\,^2D_{3/2}$	0.08	$5\,^2P_{3/2}$-$7\,^2D_{5/2}$	0.03
Tl I	$6\,^2P_{3/2}$-$6\,^2D_{5/2}$	0.37	$6\,^2P_{3/2}$-$7\,^2D_{5/2}$	0.08	$6\,^2P_{3/2}$-$8\,^2D_{5/2}$	0.03
	$6\,^2P_{1/2}$-$6\,^2D_{3/2}$	0.34	$6\,^2P_{1/2}$-$7\,^2D_{3/2}$	0.09	...	

[a]Reference 15.

persion method by Penkin and Shabanova.[12–14] Theoretical calculations by Gruzdev[16] have been based on the single-configuration Coulomb approximation originally introduced by Burgess and Seaton.[18] The close agreement between calculated and experimental oscillator strengths for the sharp series of these third-group neutral atoms indicates that in such cases, the single-configuration Coulomb approximation is a good model. Gruzdev[16] has found that in general, the quantum defects of the $m\,^2S_{1/2}$ level show the same behavior for Al I, Ga I, In I, and Tl I and takes this as the criterion for the applicability of the single-configuration approximation.

Gallagher and Lurio[11] reported lifetimes for the $7\,^2S_{1/2}$ state in Tl I and the $6\,^2D_{3/2}$ in Tl I by optical double-resonance technique and level crossing. These results deviate by less than 10% from the present results. From some of the oscillator-strength values reported in the literature, Gallagher and Lurio[11] have constructed a table of thallium-oscillator strengths, and some of these results are shown in Table VII, compared with the present data of f values and estimated by means of the BD tables.[19] A remarkable agreement between the various oscillator strengths are observed, with the exception of the $6\,^2P_{3/2,1/2}$-$7\,^2S_{1/2}$ transitions, for which the BD values are more than a factor of two off. This is in agreement with the assumption that the Coulomb approximation is less accurate for strongly bound states. The values obtained from the BD tables are single-valence electron-transition probabilities; this means that configuration mixing in the thallium states causes only a small correction to the single-valence electron case.

For the $n\,^2P_{1/2,3/2}$-$m\,^2D_{3/2,5/2}$ transitions, the evaluated f values (Table VI) show a characteristic feature. The sequence Ga I, In I, and Tl I (but not Al I) shows the same f value for similar transitions, in this case transitions to the lowest ^2P states from various ^2D states. When increasing the main number m, a decrease in the f value is observed, but still the f value is constant within a homologous sequence. For the transition $3\,^2P_{3/2}$-$3\,^2D_{5/2}$ in Al I the f value is about a factor of 2 smaller than the same transition in the other members of the sequence. Gruzdev[16] has studied the energy dependence of the quantum defects of ^2D terms. The low f value for $3\,^2P_{3/2}$-$3\,^2D_{5/2}$ transition might be due to the location of the $3s\,3p^2\,^2D$ level, which according to Gruzdev[16] might occupy the place that previously has been attributed to the $4d\,^2D$ term. Gruzdev's argument is based on the study of the energy dependence curve of the quantum defect of the $m\,^2D$ terms in Al I, which shows a change of curvature at the $4\,^2D$ state.

Oscillator strengths for the diffuse series in Al I, Ga I, In I, and Tl I have been studied by the anomalous dispersion (Penkin and Shabanova[12–14]) and theoretically by Gruzdev.[16] The ratio of the calculated values to those found experimentally varies between 0.012 and 9.3. No systematic trend seems present.

When the values from Gruzdev's theoretical estimates are compared with those obtained from this study (Table VIII) identical $f_{\text{theor}}/f_{\text{beam-foil}}$ ratios are obtained for homologous transitions. However, f values obtained by the hook method[12–14] normalized to the beam-foil f values show no consistency with the exception of the resonance transitions.

TABLE VII. Thallium oscillator strengths.

Transition	f value (this work)	f value (Ref. 11)	BD values (Ref. 19)
$6\,^2P_{3/2}$-$7\,^2S_{1/2}$	0.14	0.151	0.09
$6\,^2P_{1/2}$-$7\,^2S_{1/2}$	0.13	0.133	0.05
$6\,^2P_{3/2}$-$6\,^2D_{5/2}$	0.37	0.346	0.39
$6\,^2P_{1/2}$-$6\,^2D_{3/2}$	0.34	0.290	0.29
$6\,^2P_{3/2}$-$7\,^2D_{5/2}$	0.08	0.081	0.10
$6\,^2P_{1/2}$-$7\,^2D_{3/2}$	0.09	0.074	0.08
$6\,^2P_{3/2}$-$8\,^2D_{5/2}$	0.03	0.028	0.04

TABLE VIII. A comparison of the evaluated f values with previous data.

Spectrum	Transition	$\frac{f_{\text{theor}}}{f_{\text{beam-foil}}}$ [a]	$\frac{f_{\text{hook}}}{f_{\text{beam-foil}}}$ [b]
Ga I	$4\,^2P_{1/2,3/2}$-$4\,^2D_{3/2,5/2}$	1.9	1.0
In I	$5\,^2P_{1/2,3/2}$-$5\,^2D_{3/2,5/2}$	2.0	1.1
Tl I	$6\,^2P_{1/2,3/2}$-$6\,^2D_{3/2,5/2}$	1.8	0.9
Ga I	$4\,^2P_{3/2}$-$5\,^2D_{5/2}$	2.4	0.5
In I	$5\,^2P_{1/2,3/2}$-$6\,^2D_{3/2,5/2}$	2.5	0.7
Tl I	$6\,^2P_{1/2,3/2}$-$7\,^2D_{3/2,5/2}$	2.3	1.0
In I	$5\,^2P_{3/2}$-$7\,^2D_{5/2}$	2.6	0.3
Tl I	$6\,^2P_{3/2}$-$8\,^2D_{5/2}$	2.6	1.0

[a]Reference 16. [b]References 12–14.

The present investigation shows that Gruzdev's f values are reliable on a relative scale, whereas the absolute values are a factor 2–2.5 too high.

Ionized Ga, In, Tl have not previously been studied experimentally with respect to f values. Only Helliwell[3] has reported theoretical f values, using a modified self-consistent-field approach, which uses experimental term values to eliminate the need for calculating wave functions for the core electrons. This semiempirical approach is compared with f values obtained from beam-foil lifetime data in Table IX. The agreement is within 20–30%.

TABLE IX. Beam-foil data.

	Lower state	Upper state	λ (Å)	f_{expt}	f_{theor} [a]
Al II	$3p\,^1P$	$4s\,^1S$	2816	0.067	0.05
Ga II	$4p$	$5s$	2780	0.061	0.07
In II	$5p$	$6s$	2945	0.062	0.07
Tl II	$6p$	$7s$	3092	0.102	0.08

[a]Reference 3.

The present data show that when configuration mixing is less important, identical f values are found for the same transition in all the members of a homologous sequence. The beam-foil technique presents an ideal tool for systematic investigation of homologous and isoelectronic sequences, but it has certain limitations. It is difficult to study excited levels with higher main quantum numbers than those described in the present work. The intensity of the higher terms is small and the lifetimes relatively long. Therefore the purity of the ion beam is of crucial importance for the study of higher terms, so contamination of spectral lines originating from very small currents of molecular ion beams is avoided.

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