

Lifetimes of Excited Levels in PI–PV

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Abstract

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We have studied the beam-foil spectra of phosphorus between 600 and 2 200 Å and measured radiative lifetimes for 21 excited terms in PI–PV. We discuss the merits of several methods for evaluating the decay constants and compare the results with theoretical transition probabilities as well as with recent experimental studies of oscillator strengths in the PI, Si I, Al I, Mg I. and Na I isoelectronic sequences.

1. Introduction

A program of systematic studies of oscillator strengths in the Na I, Mg I, Al I, Si I, and PI isoelectronic sequences is underway at the Research Institute for Physics. The method of beam-foil spectroscopy is being used, and the results for Na, Mg, Al, and Si in various stages of ionization have been reported previously [1, 2]. In this paper we discuss the extension of the work to phosphorus, which also has been studied by Andersen et al. [3] with the beam-foil method. Whereas Ref. [3] investigated the air region, the present paper places the emphasis on the v.u.v. Because of the limited resolution in beam-foil spectra, especially at moderate beam intensities and low particle velocities, we present no wavelength analyses but have concentrated on decay measurements of excited levels, in particular those which combine with the ground state by resonance transitions. For such low-lying states, experimental investigations are valuable, since the theoretical calculations are complicated by configuration mixing effects.

The possibility of various systematic errors in decay-time measurements with the beam-foil method has been emphasized recently [4]. The most serious of these uncertainties is probably the cascade repopulation of the decaying level under study. We have applied several results of recent analyses [2, 5, 6] to reduce such uncertainties and have also developed new approaches for deducing more reliable lifetimes from the measured decay curves.

2. Experiment

Beams of P⁺⁺ and P⁺⁺⁺ were obtained from the 80 kV isotope separator of the Research Institute for Physics. Typical beam currents were 1–2 μA. We used 10 μg/cm² carbon foils to excite the ions and dispersed the radiation after the foil with a 1-meter vacuum monochromator, equipped with a Bendix Channeltron (600–1 000 Å) or a sodium salicylate coated EMI 6 256 photomultiplier (800–2 200 Å). We also recorded a few spectra between 3 000 and 6 000 Å, using a Jarrell–Ash 0.25 m monochromator. The pulses from the detectors were fed into an ELSICINT single

channel analyzer, the ratemeter of which was used for spectral scans. Decay curves were obtained by pulse-counting for equal times at various points downstream from the foil, while the beam current was held constant to within 5%. Every lifetime was measured until at least three reproducible decay curves were obtained.

3. Decay curve analysis

We used several alternative techniques to extract lifetimes from the decay curves obtained. These methods could greatly reduce the uncertainties which arise from cascade repopulation, subtraction of random noise, line blending, and statistical fluctuations. We applied new and exact analytical methods, as well as refinements of the traditional curve-fitting techniques. Cascade contributions are expressed in terms of the replenishment ratio, $R(t)$ which is defined in Ref. [5]. Its role in curve fits is described in Ref. [6] and in cascade analysis in Ref. [2].

3.1. Cascade analysis of integrated decay curves

Wherever possible, the decay curves of various correlated levels in a decay scheme were measured under similar conditions. In addition to the obvious advantage of allowing cascade lifetimes to be traced, this permits the use of an exact cascade analysis technique, introduced and discussed in Refs. [2] and [6]. By this procedure arbitrarily normalized primary and cascade decay curves can be integrated over various intervals to generate a family of linear relationships between the primary lifetime τ_1 and the initial replenishment ratio, $R(0)$. If a single cascade dominates, both τ_1 and $R(0)$ can be determined by the intersection of a family of lines on a τ_1 versus $R(0)$ plot. As an example of this technique Fig. 1 shows a diagram obtained from the decay curves of the $3s3d^3D$ term in P IV and its cascade from the $3s4p^3P$ term.

However, in many of the cases studied here, the cascade transitions were either heavily blended with (or masked by) other lines, or they fell outside our detectable wavelength region. Therefore other techniques were developed, which increased the amount of information extracted from the primary decay curves.

3.2 Differentiated decay curve analysis

In several cases the primary lifetime, obtained from curve fits, is very sensitive to uncertainties in the fitted values of the longer-lived exponentials and to the background subtracted. Furthermore, it is difficult to obtain an accurate value for the random background, since it may contain foil- and beam-associated components, and therefore can be confused with long-lived

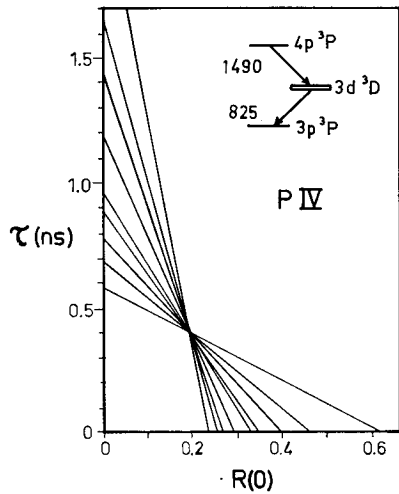


Fig. 1. Graphical solution of the linear parametric relationships between the lifetime and the replenishment ratio of the $3s3d^3D$ term in P IV, generated by cascade analysis. Each line represents a separate choice of end points for the integration of primary and cascade decay curves.

cascades or blends. However, the average random background should be the same for all data points, since data were accumulated for equal times while the beam current was kept constant. Thus the intensity $I^{(m)}(t)$, which may contain blending and random noise in addition to the desired decays, should have the form

$$I^{(m)}(t) = \sum_i C_i \exp(-t/\tau_i) + B \quad (1)$$

If we compute the derivative,

$$dI^{(m)}/dt = -\sum_i (C_i/\tau_i) \exp(-t/\tau_i) \quad (2)$$

we notice that the background contribution B disappears in the differentiated form and the long-lived exponential coefficients in the admixture are decreased in accord with the appropriate lifetime ratios. Thus, in the absence of growing-in cascades or blends with lines from shorter-lived levels, differentiation of the decay curve should make the lifetime of the level studied, τ_1 , more dominant. Many of our decay curves were sufficiently accurate, and the data points sufficiently closely spaced, to permit numerical differentiation once, twice, or even three times. As an example, the original and differentiated decay curves of the $3p^24s^4P$ term in P I are shown in Fig. 2. Note that the same exponentials occur in both curves, but in the differentiated curve the flat background has vanished, and the cascade contribution is reduced by a factor which equals the ratio of primary to cascade lifetime.

3.3 Logarithmic derivative analysis

In some cases the fluctuations in the tails of the decay curves introduced uncertainties into curve fits even when cascading was rather light. Here it was often possible to extract the lifetime from a study of the behavior of the logarithmic derivative of the decay curve (freed of background and blending contributions) near $t=0$, with the tails entering only through a determination of the replenishment ratio. The population equation for a repopulated level,

$$dN_1/dt = \sum_{i=2} N_i(t) A_{i1} - N_1(t)/\tau_1 \quad (3)$$

can be rewritten in terms of the replenishment ratio $R(t)$ as

$$dN_1/dt = [R(t) - 1] N_1(t)/\tau_1 \quad (4)$$

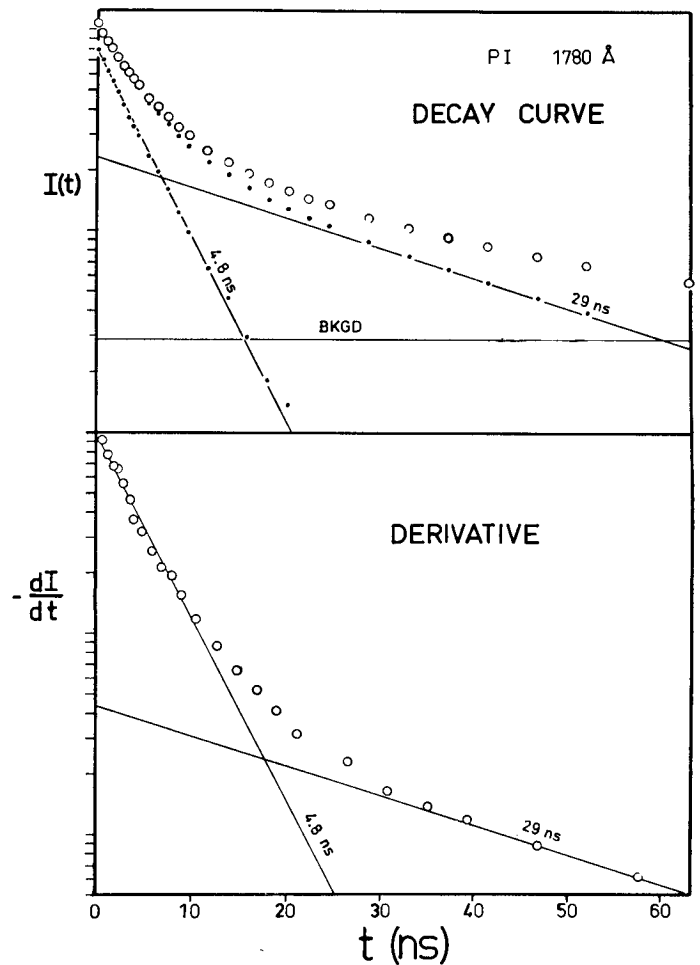


Fig. 2. Exponential fits to the measured decay curve and its numerical derivative for the $3p^24s^4P$ term in P I. Both curves contain the same exponentials, but in the differentiated curve the background has vanished and the relative cascade contribution has been reduced by a factor of 4.8/29.

and solved for τ_1 in terms of the logarithmic derivative of the population $N_1(t)$, or equivalently, its decay curve $I_1(t)$, since both have the same time dependence. This gives

$$\tau_1 = [1 - R(t)] / [-d(\ln I_1)/dt] \quad (5)$$

If a portion of the decay curve can be found where the logarithmic derivative can be reliably calculated numerically, and where the replenishment ratio is only weakly sensitive to the primary lifetime, then Eq. (5) can be used to extract the lifetime. Table I lists the logarithmic derivatives and replenishment ratios (obtained from a preliminary curve fit) for the decay curve of the P IV $3s3p^1P$ term, as a function of distance from the foil. Notice that whereas the logarithmic derivative and replenishment ratio vary widely, the value of τ_1 obtained from Eq. (5) is quite stable.

3.4. Data averaging

The less favourable signal to noise ratio on the tails of our decay curves could often cause substantial statistical uncertainties in the lifetimes obtained from curve-fitting. In the region of wavelength overlap between the Channeltron and the phototube, we found that the former gave more reliable decay curves. In spite of lower quantum efficiency, the fluctuations on the tails were very much reduced with the Channeltron, due to its low noise. The statistical fluctuation of a signal S , obtained after the subtraction of a background B , is $\Delta S = (S + 2B)^{1/2}$, and S/B often varied from 10^4 to 10^{-1} for the measured decay curves. Since uniform

Table I. Determination of the mean life of the $3s3p^1P$ term in PIV from values of the logarithmic derivative and replenishment ratio at various distances from the foil

x (mm)	$R(t)$	$-d(\ln I)/dt$ (ns ⁻¹)	τ_1 (ns)
0.125	0.222	3.58	0.217
0.375	0.400	2.73	0.219
0.625	0.603	1.82	0.221
0.875	0.760	0.94	0.255
1.125	0.820	0.59	0.264
1.375	0.900	0.52	0.192
1.625	0.905	0.39	0.230
1.875	0.918	0.38	0.242
2.125	0.920	0.30	0.265

statistics would require prohibitively long counting times, we chose to keep the counting time constant and to improve statistics on the tails by a selective averaging process.

The decay curve tails are dominated by exponentials corresponding to lifetimes greater than the spacing of the data points, Δt . Therefore, appropriately far on the tails, we averaged each data point with those adjacent to form

$$\bar{I}(t) = [I(t - \Delta t) + nI(t) + I(t + \Delta t)]/(n + 2) \quad (6)$$

In general, n was set equal to one, but when a derivative was to be performed, it was given some other value so that the difference quotient would involve several points. When the intensities conform to multi-exponential forms, the error introduced into the functional form by the averaging is of second order in $\Delta t/\tau_i$, but care must be taken that fluctuations are not smoothed into non-physical bumps.

4. Results

Fig. 3 shows two examples of the spectra, obtained with the salicylate-coated photomultiplier. The lower section has been taken at 140 keV (using P⁺⁺ incoming ions) and the upper part was obtained when 240 keV P⁺⁺⁺ ions were sent through the foil. (Singly-charged ions were also available, but at 70–80 keV the foils could be bombarded only a few minutes before breaking.) The wavelengths and ionization states of the strongest lines have been indicated. We notice that several P I transitions are quite prominent at 140 keV and they can also be clearly seen at the higher energy. Also P II and P III transitions can be conveniently studied at either energy, whereas the higher energy favoured the production of P IV and P V transitions. It is interesting to notice that the P V transitions are so prominent in the spectra at these low energies (cf. also Ref. [3]). A comparison of our work with the Si-study of Berry et al. [2] shows that in both cases it was very easy to ionize all but one of the $n = 3$ electrons, leaving the bound one in an excited state.

In the following we give a more detailed discussion of the transitions observed and the lifetimes measured.

P I

While our spectra showed all expected doublet transitions between the $3p^3$, $3p^23d$, and $3p^4$ configurations, the most intense doublet transition was that at 1859 Å ($3p^3^2D-3p^24s^2D$). In the quartet system several resonance lines were observed, of which the $3p^3^4S-3p^24s^4P$ multiplet around 1780 Å was particularly strong at lower energies. For these two strongest lines we followed the intensity decays. Table II gives the results of our lifetime

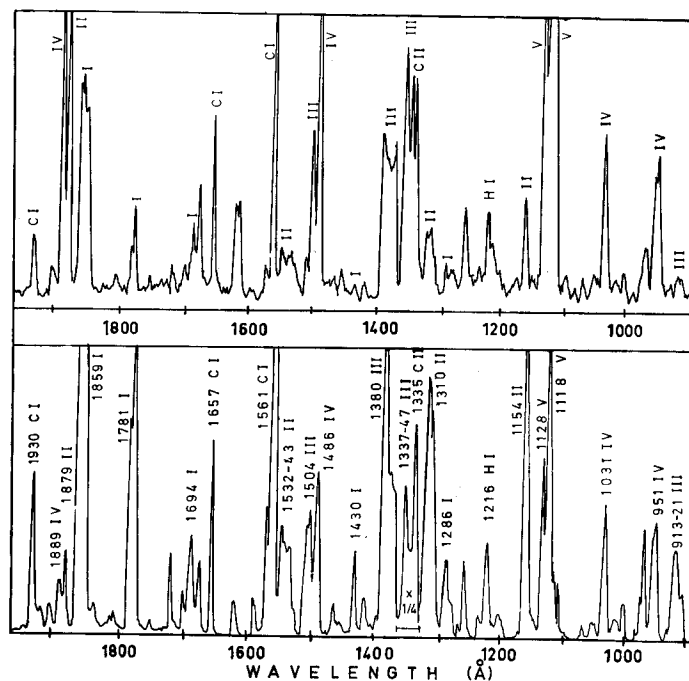


Fig. 3. Survey spectra, obtained with a salicylate coated photomultiplier. The lower scan was made with 140 keV incident ions and the upper with 240 keV incident ions. The strongest phosphorus transitions have been indicated by wavelength and ionization state. Note that the gain is different between 1330 and 1350 Å in the lower scan.

measurements, whereas the corresponding oscillator strengths are shown in Table III. The 1859 Å decay curve was decomposed into two exponentials, the steeper of which corresponds to a lifetime of 3.6 ± 0.4 ns for the $4s^2D$ term, which is slightly longer than the experimental value 2.9 ± 0.4 ns, obtained by Savage and Lawrence [7], who used the phase-shift technique. Lawrence [8] has also made intermediate-coupling calculations for this transition and found a theoretical value of 2.89 ns for the $4s^2D$ term. We tried several analytical methods for the decay of the 1780 Å line. Fig. 2 shows that the differentiated decay curve made it possible to eliminate the background and follow the decay over a longer time interval. Our lifetime of 4.8 ± 0.5 ns is in good agreement with Lawrence's calculated value, 4.6 ns [8] and in reasonable accord with the previous experimental number, 4.0 ± 0.5 ns [7]. The main cascading into the $4s^4P$ term is from the $3p^2^3P-3p^3^3D$ multiplet (1532–1543 Å) which was quite intense in Martin's spectra [10], only was moderately excited in the present work. This apparent discrepancy may be due to our long mean lifetime of the $3p^3^3D$ term, 45 ± 10 ns. Savage and Lawrence [7] obtained a still higher value, 78 ± 8 ns with the phase-shift method. The experimental oscillator strengths for the $3p^2^3P-3p^3^3D$ transition in the Si I isoelectronic sequence show irregular variations with $1/Z$. For Si I the f -value is 0.068 [9] and for P II we obtained 0.013 ± 0.003 , whereas Ref. [7] gives $f = 0.0076$. Increased f -values can be noted for S III ($f = 0.022$), Ref. [11], and for Cl IV ($f = 0.044$), Ref. [12]. It would be interesting to study

P II

The strongest P II transitions in the beam-foil spectra were combinations between $3p^2$ and $3p^3$ configurations. The singlet transitions were still fairly weak, whereas the corresponding triplet transitions showed higher intensities. It is interesting to notice that the $3p^2^3P-3p^3^3D$ multiplet (1532–1543 Å) which was quite intense in Martin's spectra [10], only was moderately excited in the present work. This apparent discrepancy may be due to our long mean lifetime of the $3p^3^3D$ term, 45 ± 10 ns. Savage and Lawrence [7] obtained a still higher value, 78 ± 8 ns with the phase-shift method. The experimental oscillator strengths for the $3p^2^3P-3p^3^3D$ transition in the Si I isoelectronic sequence show irregular variations with $1/Z$. For Si I the f -value is 0.068 [9] and for P II we obtained 0.013 ± 0.003 , whereas Ref. [7] gives $f = 0.0076$. Increased f -values can be noted for S III ($f = 0.022$), Ref. [11], and for Cl IV ($f = 0.044$), Ref. [12]. It would be interesting to study

Table II. Radiative lifetimes in *P I–P V*

Spectrum	Wavelength (Å)	Transition	Lifetime of upper level (ns)			Cascade Lifetimes (ns)	Replenishment ratio
			This work	Other experiments	Theory		
P I	1 859	$3p^3\ ^2D - 3p^24s\ ^2D$	3.6 ± 0.4	2.9 ± 0.4^a	2.89^b	23	0.15
P I	1 780	$3p^3\ ^4S - 3p^24s\ ^4P$	4.8 ± 0.5	4.0 ± 0.5^a	4.60^b	29	0.18
P II	1 308	$3p^2\ ^3P - 3p^3\ ^3P$	9.0 ± 0.5	6.4 ± 0.8^a	—	—	0.00
P II	1 539	$3p^2\ ^3P - 3p^3\ ^3D$	45 ± 10	78 ± 8^a	—	—	0.00
P II	1 880	$3p^3\ ^1D - 3p4f\ ^1F$	2.8 ± 0.3	—	—	14	0.14
P II	4 599	$3p4p^3D - 3p4d^3F$	5.0 ± 0.4	—	5.0^c	—	0.00
P III	920	$3p^2\ ^3P - 3p^2\ ^2P$	0.20 ± 0.05	—	—	0.7; 6.5	0.13
P III	1 341	$3p^2\ ^3P - 3p^2\ ^2D$	14 ± 2	—	$0.71^{c,d}; 120^e$	—	0.00
P III	1 380	$3p^2\ ^2D - 3p^3\ ^2D$	1.8 ± 0.4	—	—	—	0.00
P III	1 502	$3p^2\ ^2D - 4p^2\ ^3P$	2.8 ± 0.2	3.1^f	4.2^f	0.5	1.4
P III	1 618	$3d^2\ ^2D - 4f^2\ ^2F$	0.70 ± 0.15	—	—	3; 15	0.23
P III	784	$3p^2\ ^4P - 3p4s\ ^4P$	0.5 ± 0.2	—	—	3.5	0.25
P IV	951	$3s^2\ ^1S - 3s3p\ ^1P$	0.22 ± 0.02	—	$0.254^{c,g}$	1.7; 18	0.15
P IV	1 889	$3s3p\ ^1P - 3p^2\ ^1D$	8.2 ± 0.8	—	—	—	0.00
P IV	756	$3p^2\ ^1D - 3p3d\ ^1D^h$	0.5 ± 0.3	—	$0.30^{c,g}$	0.9; 6	0.30
P IV	826	$3s3p\ ^3P - 3s3d\ ^3D$	0.36 ± 0.05	—	$0.215^{c,g}$	1.5; 3.3	0.25
P IV	877	$3s3d\ ^3D - 3s4f\ ^3F$	0.4 ± 0.1	—	—	1; 13	0.36
P IV	1 030	$3s3p\ ^3P - 3p^2\ ^3P$	0.32 ± 0.03	—	$0.33^{c,i}$	1.8	0.06
P IV	1 490	$3s3d\ ^3D - 3s4p\ ^3P$	1.1 ± 0.3	1.9^f	1.25^f	3.3	0.13
P V	1 121	$3s^2\ ^3S - 3p^2\ ^3P$	0.70 ± 0.15	—	$0.84^{c,i}$	0.4; 2.8	0.84
P V	865	$3p^2\ ^3P - 3d^2\ ^2D$	0.30 ± 0.06	—	$0.27^{c,i}$	0.9; 5	0.16

^a Ref. [7]; ^b Ref. [8]; ^c Ref. [9]; ^d Ref. [22]; ^e Ref. [14]; ^f Ref. [3]; ^g Ref. [19]; ^h Classification based on Ref. [15]. In view of our reclassification of the 1 889 Å line, this assignment is uncertain. ⁱ Ref. [18].

this transition in Ar V and higher ions, so as to determine the maximum of f . Unfortunately this sequence has not been calculated with respect to configuration mixing. Measurements on the P II multiplet at 1 308 Å ($3p^2\ ^3P - 3p^3\ ^3P$) yielded a value of 9.0 ± 0.5 ns, which is longer than that given in Ref. [7]. We also measured the decays of the $3p4f\ ^1F$ and $3p4d\ ^3F$ terms (Table II). Comparison with previous work is not possible for the former, whereas the $3p4d\ ^3F$ lifetime has been estimated, using the Coulomb approximation [9]. Our work and theory seem to give similar results. However, the probability for the branch $3p^2\ ^3P - 3p4d\ ^3F$ (801 Å) has not been calculated, but according to Martin [10], this line is relatively weak. There were no indications of this line in our spectra.

P III

As Fig. 3 shows, several P III multiplets could be observed. Radiative decays were measured for six levels in P III (Table II).

Table III. Oscillator strengths in *P I–P V*

Spectrum	Wave-length (Å)	Transition	Absorption oscillator strength		
			This work	Other experiments	Theory
P I	1 859	$3p^3\ ^2D - 3p^24s\ ^2D$	0.15 ± 0.02	0.18 ± 0.02^a	0.18^b
P I	1 780	$3p^3\ ^4S - 3p^24s\ ^4P$	0.30 ± 0.03	0.36 ± 0.04^a	0.307^b
P II	1 308	$3p^2\ ^3P - 3p^3\ ^3P$	0.029 ± 0.002	0.040 ± 0.005^a	—
P II	1 539	$3p^2\ ^3P - 3p^3\ ^3D$	0.013 ± 0.003	0.0076 ± 0.0008^a	—
P III	920	$3p^2\ ^3P - 3p^2\ ^2P$	0.6 ± 0.2	—	—
P III	1 341	$3p^2\ ^3P - 3p^2\ ^2D$	0.032 ± 0.005	—	$0.64^{c,d}, 0.0033^e$
P III	784	$3p^2\ ^4P - 3p4s\ ^4P$	0.18 ± 0.07	—	—
P IV	951	$3s^2\ ^1S - 3s3p\ ^1P$	1.8 ± 0.2	—	$1.60^{c,f}$
P IV	1 889	$3s3p\ ^1P - 3p^2\ ^1D$	0.11 ± 0.01	—	$0.12^{c,f}$
P IV	826	$3s3p\ ^3P - 3s3d\ ^3D$	0.47 ± 0.07	—	$0.796^{c,f}$
P IV	877	$3s3d\ ^3D - 3s4f\ ^3F$	0.40 ± 0.10	—	—
P IV	1 030	$3s3p\ ^3P - 3p^2\ ^3P$	0.50 ± 0.05	—	$0.481^{c,g}$
P V	1 121	$3s^2\ ^3S - 3p^2\ ^3P$	0.80 ± 0.16	—	$0.67^{c,g}$
P V	865	$3p^2\ ^3P - 3d^2\ ^2D$	0.63 ± 0.13	—	$0.69^{c,g}$

^a Ref. [7]; ^b Ref. [8]; ^c Ref. [9]; ^d Ref. [22]; ^e Ref. [14]; ^f Ref. [19]; ^g Ref. [18].

We obtained a very short lifetime for the $3p^2\ ^3P$ term, 0.20 ± 0.05 ns, which is near our limit for short decay times. However, this value was reproducible when various techniques, described in Section 3, were used. No theoretical f -values for the $3p^2\ ^3P - 3p^2\ ^2P$ transition in P III are available, but we notice that our experimental value, 0.6 ± 0.2 , is relatively close to the theoretical f -value of 0.93 for the same transition in Si II [13]. Of course, such a comparison can only be a rough estimate, since fortuitous agreements may occur. The $3p^2\ ^3P - 3p^2\ ^2D$ transition in the Al I isoelectronic sequence has been theoretically studied by Weiss [13], Froese Fischer [14] and others. The thorough analysis in Ref. [14] shows that the two 2D states, $3s3p^2$ and $3s^23d$ are heavily mixed for Si II and P III, which accounts for a very long theoretical lifetime, 120 ns [14] for the $3s3p^2\ ^2D$ term in P III. Our decay curves showed a weak, rapid component of 1.4 ns, which we interpret as the contribution from the C II line at 1 335 Å, originating from foil-ejected carbon. The main component, 14 ± 2 ns, represents most probably the lifetime of the $3p^2\ ^2D$ term. The discrepancy with Ref. [14] is not too distressing; Froese Fischer points out that the theoretical f -value may have a substantial uncertainty, depending on where between Si II and P III the transition matrix element passes zero. Unfortunately the $3p^2\ ^3P - 3p^2\ ^2D$ transition was too weak in Si II to allow decay measurements [2], but a comparison between theory and experiment is possible for S IV [11] and Cl V [12]. Whereas for S IV the measured $3p^2\ ^2D$ lifetime is a factor of two shorter than the theoretical prediction [14], the corresponding Cl V values agree to within 30%. The beam-foil experiments largely confirm the shape of the theoretical f versus $1/Z$ graph [14], but the deviations for P III and S IV may indicate a slightly different zero point for the multiplet strength. Our measured lifetime for the $4f^2\ ^2F$ term of P III corresponds to a probability of $14 \times 10^8\ s^{-1}$ for transitions from this level. This transition has been calculated by Weiss [13] for Al I and Si II and in both cases the f -values were found to be 0.5. The P III measurement might indicate a somewhat higher f -value, but since the $4f^2\ ^2F$ term also can decay to the displaced system, for example to $3p^2\ ^2D$, no definite conclusions

can be drawn. Our decay measurements for the $4p^2P$ level give a mean lifetime of 2.8 ± 0.2 ns, which agrees with the results of Andersen et al. (3), who measured the decay of this term to $4s^2S$ and $3d^2D$.

P IV

Several P IV transitions were observed in our wavelength range. The resonance transition $3s^2S-3s3p^1P$ (951 Å) was relatively strong at our highest energy. We also observed a strong transition at 1 889 Å, which according to Robinson (15) is the $3s3p^1P-3s3d^1D$ transition, whereas the $3s3p^1P-3p^2D$ combination was supposed to be at 1 640 Å. In his study of the Si III spectrum, Toresson (16) pointed out that this assignment is probably in error in P IV. Using recent classifications of a 1 501 Å transition in S V [17] and a 1 246 Å line in Cl VI (Ref. [12]) as the $3s3p^1P-3p^2D$ transition, we assign the observed line at 1 889 Å to this combination in P IV. No transition could be seen in the beam-foil spectra at 1 640 Å. A few P IV triplet transitions were observed with the Channeltron and their decay times could be measured.

As Table II shows, several of the P IV mean lives were found to be comparatively short, but applications of the analytical techniques described earlier were quite successful in reducing the uncertainties. All reported lifetimes of less than one ns were determined from both the original and the differentiated decay curves. The cascade effects were sharply reduced in the differentiated curves. In the case of the $3p^2P$ term, the decay curve (1 030 Å) could be numerically differentiated four successive times, with cascade contributions reduced further and further, but each time containing a main exponential, corresponding to a lifetime of 0.32 ± 0.03 ns. Logarithmic derivatives were also computed, which confirmed and sharpened the determinations. Table I gives the logarithmic derivatives and the replenishment ratios for the decay of the $3s3p^1P$ term. We analyzed six separate decay curves, and each reproduced the dependences shown in Table I to within a few percent. We also measured the decay of the $3s3d^3D$ term as well as the lifetimes of its main cascading levels, $3s4f^3F$ and $3s4p^3P$. An integrated decay curve analysis yielded a sharp $3s3d^3D$ lifetime determination, as indicated by the intersection in the parametric plot in Fig. 1.

Generally we notice good agreement with theory [9, 18, 19] and consistency with measured lifetimes of other members of the Mg I sequence. Fig. 4 shows the variation of the f -value with $1/Z$ for the $3s^2S-3s3p^1P$ transition. Unfortunately, the experimental uncertainties are substantial, due to very short lifetimes, but there is no real disagreement with the calculations of Crossley and Dalgarno [18] and Zare [19]. A similar graph for the $3s3p^1P-3p^2D$ transition is shown in Fig. 5. The beam-foil results are in very good agreement with the calculations of Zare [19] and Weiss [13]. Much interest has been focused on this particular transition in the Mg I sequence, mainly because of the interference between $3s3d$ and $3p^2D$, which is particularly pronounced around Al II.

Whereas our results for the $3s3p^3P-3p^2P$ transition agree with theory [18], a discrepancy prevails for the $3s3p^3P-3s3d^3D$ transition, for which the experimental f -value is lower (Table III). Our oscillator strength for the $3s3d^3D-3s4f^3F$ transition, 0.40 ± 0.10 may look somewhat surprising, because the f -values for $3d-4f$ transitions are usually closer to unity. However, an experimental f -value of 0.4 was also obtained for this triplet transition in Si III [2]. Edlén [20] has discussed in detail the perturbations from the $3p3d^3F$ term to the $3snf^3F$ series in Al II. The location of the $3p3d^3F$ term is not known in P IV and it is

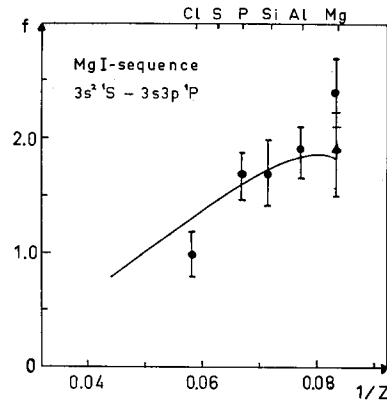


Fig. 4. Absorption oscillator strength f versus inverse nuclear charge $1/Z$ for the $3s^2S-3s3p^1P$ transition in the Mg I isoelectronic sequence. The solid line represents the theoretical predictions of Ref. [9]. The experimental data sources are: Mg, Refs. [1], [23]; Al, Ref. [1], Si, Ref. [2]; P, this work; Cl, Ref. [12]. The phase-shift measurement [23] is indicated by a triangular point; the remaining data are from beam-foil measurements.

difficult to estimate its influence on the $3s4f^3F$ lifetime, but the calculations of Weiss [21] show that for Al II the f -values are strongly affected.

P V

Transitions from four P V terms, $3p^2P$, $3d^2D$, $5f^2F$, and $5g^2G$ were clearly observed, and we found indications of a few other P V lines at our highest energy. The resonance multiplet $3s^2S-3p^2P$ was resolved into components at 1 118 and 1 128 Å, which had the expected 2:1 intensity ratio, thus indicating that the blending from the P IV $3s3p^1P-3p^2S$ transition (1 118 Å) was not severe. (Also, in the beam-foil spectra of Cl [12], the Cl VII $3s^2S-3p^2P$ transition at 800 and 813 Å was always 10–20 times as intense as the Cl VI $3s3p^1P-3p^2S$ line at 786 Å.) We measured the mean lives of the $3p^2P$ and $3d^2D$ levels in P V. Cascade analyses of the integrated decay curves did not yield well-defined intersections (between τ_1 and $R(O)$), indicating that both the $3p^2P$ and $3d^2D$ levels were fed by cascades from several terms. However, our curve fits gave consistent results, and the cascade effects were largely reduced when the decay curves were differentiated. The effects of configuration mixing

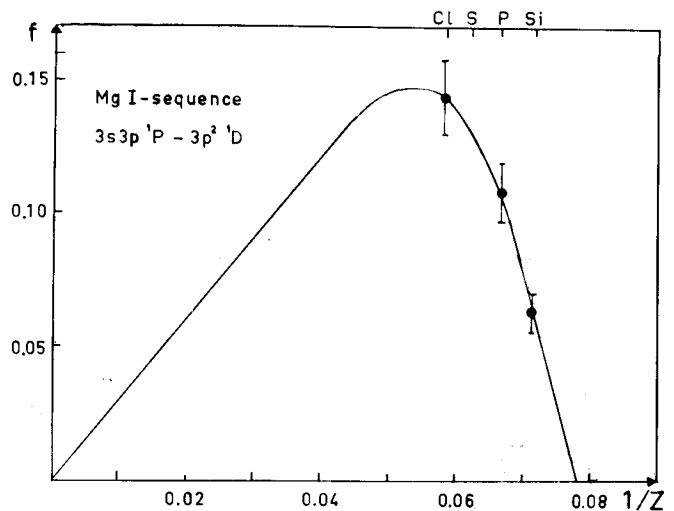


Fig. 5. Oscillator strength versus $1/Z$ for the $3s3p^1P-3p^2D$ transition in the Mg I isoelectronic sequence. The solid line represents the theoretical predictions of Ref. [9], whereas the data sources are: Si, Ref. [2]; P, this work; Cl, Ref. [12], all of which are beam-foil measurements.

are easier to command in the Na I sequence than for the other sequences discussed here, and the calculations are expected to be quite reliable [9]. Our measured lifetimes are also in good agreement with the theoretical predictions of Crossley and Dalgarno [18]. The decay times of the $3p^2P$ and $3d^2D$ terms in this sequence have now been measured with the beam-foil technique for all ions between Na I and Cl VII. The results, which are graphically displayed in Refs. [2] and [12], show that experiment and theory are usually in good agreement.

5. Conclusion

In cases where theoretical calculations of f -values have been made, reasonable agreement exists with our measured values, even when the measured lifetimes are as short as a few tenths of a nanosecond. The agreement is best for P IV and P V, indicating that the calculations on the Na I and Mg I sequences have produced reliable results. Some discrepancies between this work and theory can be noted for P III, but even here our f -values give at least qualitative support to recent configuration-interaction calculations. Our beam-foil data are also in accord with phase-shift measurements of P I and P II lifetimes. The oscillator strengths for lines in the Al I, Si I, and P I sequences show often interesting trends, and more calculations and systematic measurements are certainly needed.

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