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Experimental Transition Probabilities for Intercombination Lines in N IV, O V and F VI

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Abstract

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Lifetime measurements using the beam-foil method are reported for the $2s3p\ ^3P_{0,1,2}$ levels in N IV, O V and F VI. The $^3P_1$ level lifetime is significantly shorter than those for $^3P_0$ and $^3P_2$. This is due to the $2s^2\ ^1S_0$–$2s3p\ ^3P_1$ intercombination transition. From careful lifetime measurements at several ion energies we obtain transition probabilities of $(3.3 \pm 2.7) \times 10^6$, $(22 \pm 6) \times 10^6$ and $(88 \pm 9) \times 10^6\ \mathrm{s}^{-1}$ for this spin–forbidden transition in N IV, O V and F VI, respectively. These results are supported by theoretical analyses.

1. Introduction

The intercombination lines in the spectra of light elements are of considerable atomic-theoretical interest. In the Be I isoelectronic sequence, for instance, the spin–orbit interaction, by mixing $^1P_1$ and $^3P_1$ levels, makes it possible for the latter to combine with the $2s^2\ ^1S_0$ ground state. While the transition probability for the $2s^2\ ^1S_0$–$2s2p\ ^3P_1$ intercombination line in Be I and isoelectronic ions has been theoretically studied by many authors (see, e.g., [1–10]) only one experimental result is presently available. Using 491 MeV Fe ions from the Berkeley Super-HILAC, Dietrich et al., [11] determined the $2s2p\ ^3P_1$ lifetime in Fe XXIII, obtaining $\tau = 13 \pm 4$ ns, in reasonable agreement with theoretical predictions. Such measurements are possible only for very high ionization stages. For lower Z systems the lifetimes are far too long to permit decay-length determinations. Thus for Si XI the theoretically predicted $2s2p\ ^3P_1$ lifetime is about 3 μs [3, 10]. When 25 MeV Si ions (a typical energy needed to produce Si XI) are used the $1/e$ decay length of the $^3P_1$ level would thus be close to 40 m.

The situation is different in the He I sequence, and there exists a substantial amount of experimental information about transition probabilities for intercombination lines $1s^2\ ^1S_0$–$1s2p\ ^3P_1$ (see, e.g., [12, 13]).

The intercombination lines are of great astrophysical and plasma physical interest. The $2s^2\ ^1S_0$–$2s2p\ ^3P_1$ lines in Be-like ions have been observed in solar and stellar spectra, including those of QSO's and nebulae [14]. For a thorough discussion of the importance of intercombination lines when studying laboratory and astrophysical the review by Gabriel and Jordan [15] should be consulted.

In the present paper we will discuss another intercombination transition in the Be I sequence, namely $2s^2\ ^1S_0$–$2s3p\ ^3P_1$. Experimental determinations of its transition probability are possible already for ionization degrees as low as O V and F VI. The effect is found to be too small in N IV to permit reliable measurements, and only an approximate value can be suggested. For these ions we have studied the lifetimes of the $2s3p\ ^3P_{0,1,2}$ levels individually, using comparatively favourable spectral resolution and good counting statistics. Quantitative information about the $2s^2\ ^1S_0$–$2s3p\ ^3P_1$ transition probability is then obtained by comparing the $^3P_1$ lifetime with those for $^3P_2$ and $^3P_0$. The latter two should be practically identical, as discussed below. While there are many theoretical results for the $2s^2\ ^1S_0$–$2s2p\ ^3P_1$ transition probability [1–10], as already noted, no predictions for the $2s^2\ ^1S_0$–$2s3p\ ^3P_1$ line strength have appeared in the literature. In view of this fact we have also performed some calculations using a Hartree-Fock approximation with a limited number of configurations.

2. Experiment

The measurements were made using the 3 MV Pelletron tandem accelerator (National Electrostatics Corp.) at the University of Lund. Beams of N, O and F, obtained from the duoplasmatron ion source, were directed, after acceleration and mass analysis, through thin carbon foils in the target chamber. The light emitted by the foil-excited particles was analyzed with a McPherson 2051 1 m Czerny–Turner monochromator, equipped with an N_2-cooled EMI 9789 photomultiplier at the exit slit. The $2s3s\ ^3S_1$–$2s3p\ ^3P_{0,1,2}$ transitions have the following wavelengths (in Å) 3484.96, 3482.99, 3478.71 in N IV [16] and 2789.85, 2786.99, 2781.01 in O V [17]. For F VI only the wavelengths 2323.35 and 2315.39 Å for the two strongest components of the $2s3s\ ^3S$–$2s3p\ ^3P$ triplet are given in the literature [18]. Since our aim was to measure the lifetimes of the $2s3p\ ^3P$, $J = 0$, 1, 2 levels individually, we needed higher wavelength resolution than that used in the majority of beam-foil experiments at MeV energies. To achieve this we refocussed the monochromator for a fast-beam light source [19] thereby effectively reducing the Doppler broadening of spectral lines arising from the finite acceptance angle of the monochromator. Such a refocussing is usually obtained in practice by moving the exit slit of the optical instrument; in our experiment the same effect was accomplished by moving the concave mirror closest to the exit slit along its normal. The optimum displacement was found using the formula in [19] and small empirical adjustments. Using this technique the linewidths were reduced from about 10 Å to slightly more than 1 Å. Additional improvements might have been possible by reducing the slit widths from 200 μ to perhaps 50–100 μ but for the present purpose the merits would not have compensated for the reduction of signal.

The spectral scans and lifetime measurements were performed with an automated on-line system, specially constructed for

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fast-beam atomic physics experiments [20]. Briefly, the system consists of an Alpha LSI 2-20 minicomputer, a Tektronix 4006 terminal and an experiment control unit, designed and built in our laboratory. The programs and data are stored in a unit which consists of two Pertec FD 511 floppy-disc drives and a floppy-disc controller. The control unit communicates with scalers and switches as well as with stepmotors used for translating the foil (lifetime measurements) and rotating the grating (spectral scans).

When recording spectra or decay curves each data point was normalized to a preset amount of beam charge, collected in a Faraday cup, attached to the target chamber. Spectral scans and lifetime measurements were performed using beams of 2.9 MeV nitrogen, 2.5, 3.0 and 4.0 MeV oxygen and 3.0 and 3.5 MeV fluorine. These energies were determined very accurately, prior to foil interaction, by means of an NMR probe. The energy loss in our 10 and 20 μg cm^{-2} foils was calculated using the tables of Northcliffe and Schilling [21] for electronic energy loss. The nuclear stopping was found to be negligible at our MeV energies, using the data in [22, 23]. The velocity uncertainty after the foil is estimated to be substantially below 1%.

Before and after each lifetime measurement we determined the beam-dependent background by recording "decay-curves" in the vicinity of the spectral lines studied. This count rate, approximately 1 pulse/s was found to be essentially constant over a distance of 20 cm in the chamber, except for a small increase very close to the foil (possibly due to light reflections).

For O V we measured the decay of each of the three ^3P levels six times, using three different ion energies (as mentioned above). Four sets of data (for each J-level) were taken in the case of F VI, using two ion energies. Measurements as well as our theoretical estimates showed that the probability of the spin–forbidden decay is too low to permit quantitative studies for N IV for realizable data accumulation times, and we were thus forced to be content with a limited number of measurements (for $J = 1$ and $J = 2$ levels) using only one energy.

For each set of measurements all three ^3P decay curves were recorded with the same statistics. This means that the preset charge (for normalizing the data) was 1.67 times higher for the $J = 1$ state and 5 times higher for $J = 0$ than for the $J = 2$ state. The small increase in background for $J = 1$ and $J = 0$ was corrected for.

3. Data analysis and results

3.1. *Wavelengths*

The $2s3s\ ^3S_1$–$2s3p\ ^3P_{0,1,2}$ multiplet as observed in our N, O and F spectra is shown in Fig. 1. We see that all three components of the F VI triplet are intense in the beam-foil light source. In order to accurately determine the wavelength of the $2s3s\ ^3S_1$–$2s3p\ ^3P_0$ line in F VI all lines were fitted to Gaussian line profiles. We then determined the $^3S_1$–$^3P_0$ wavelength for N IV, O V and F VI, using tabulated values [16–18] for the $^3S_1$–$^3P_2$ and $^3S_1$–$^3P_1$ components. Since all three lines of the triplet are known in N IV and O V, we could thus obtain a good estimate of the error in F VI. Here we found a $^3S_1$–$^3P_0$ wavelength of 2327.23 ± 0.05 Å as an average of three independent measurements. The error estimate should be a conservative one because the $J = 1$ and $J = 0$ components are so well separated in F VI. The $^3P_1$–$^3P_2$ splitting is 148 cm^{-1} [18] and for the $^3P_0$–$^3P_1$ separation we obtain 72 cm^{-1}, i.e., there is a small deviation from the Landé interval rule, similar to that noted for N IV and O V [16, 17].

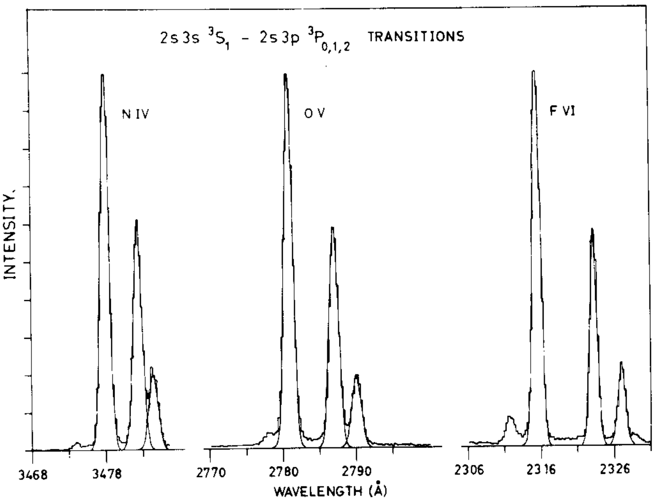

Fig. 1. Spectral scans of the $2s3s\ ^3S_1$–$2s3p\ ^3P_{0,1,2}$ multiplet in N IV, O V and F VI.

3.2. *Lifetimes*

The background on our decay curves was reduced by subtracting the time-corrected beam-dependent background point by point. Data points for which the sampling time significantly deviated from the average (e.g., due to beam fluctuations) were excluded from the analysis. The lifetimes were extracted with the help of the multi-exponential fitting program DISCRETE [24] which determines the number of exponentials as well as the lifetimes for a best and a second-best fit. The points were weighted according to statistical uncertainty and the foil-shadowed region was excluded by truncating the beginning of the decay curves until the lifetimes reached stable values.

Examples of lifetime curves for O V and F VI are shown in Figs. 2 and 3. In both figures the three curves were taken with the same statistics (about 10 000 counts/channel at the position closest to the foil). We clearly see that the $J = 1$ level has a shorter lifetime in both ions, the effect being particularly pronounced in F VI. We also observe that the decay curves are basically single exponentials. Only for large distances from the foil do we note deviations from one-exponential behaviour. This cannot be due to direct or second-order cascading because, e.g.,

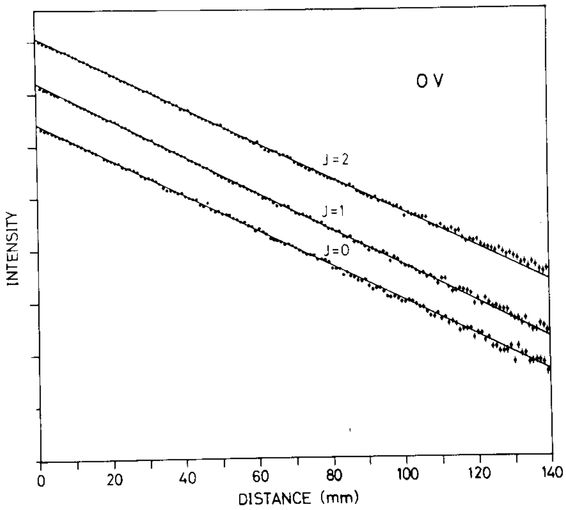

Fig. 2. Intensity decay curves for the $2s3p\ ^3P_{0,1,2}$ levels in O V. All curves were taken with the same statistics, about 10 000 counts/channel at the position closest to the foil, but are shifted for purposes of illustration. The ordinate scale is logarithmic.

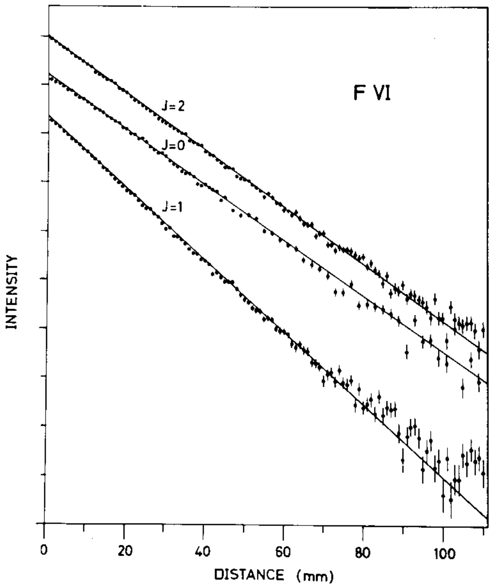

Fig. 3. Intensity decay curves for the $2s3p\ ^3P_{0,1,2}$ levels in F VI. All curves were taken with the same initial statistics, about 10 000 counts/channel and drawn as in Fig. 2.

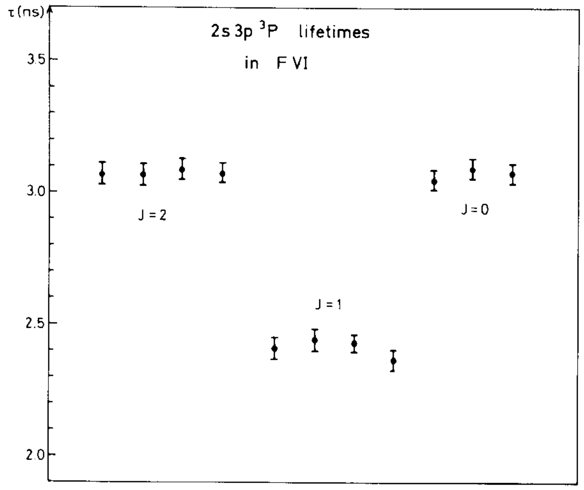

Fig. 4. Comparison of the results from the individual measurements in F VI. A fourth measurement for $J = 0$ has not been included because of systematic uncertainties. The uncertainties indicated include the statistical errors, the velocity uncertainty after the foil and an estimated effect of the error caused by background corrections.

in O V levels such as $2s3d$, $2s4d\ ^3D$, $2s4f$ and $2s5f\ ^3F$ have lifetimes much shorter than 1 ns [25, 26], Cascades from very high Rydberg states or continuum levels cannot be excluded but it is more likely that we have not been able to entirely correct for background effects. Analyses using various backgrounds and one- or two-exponential fits show that the overall effects of these background problems on our lifetime data are negligible to within quoted uncertainties.

The lifetimes obtained by us as well as a selection of previous work can be found in Table I. Of previous experimental results we only include the work of Lewis et al. [27, 28] and Druetta et al. [29] because these authors measured some of the J-states individually. There are additional lifetime results for the unresolved $2s3p\ ^3P$ term in N IV and O V [13]. For example in N IV the following values (in ns) have been reported: 7.3 ± 0.5 [30], 8.2 [31], 8.7 [32, 33] and 11.5 ± 0.8 [34]. For the unresolved multiplet in O V there is also an experimental lifetime of 4.5 ns [33]. No previous data are available for F VI.

Table I shows that our N IV and O V results are in good agreement with the measurements of Lewis et al. [27, 28], while there is a small deviation from the results of Druetta et al. [29]. It can further be noted that Refs. [28] and [29] also found that in O V the $^3P_1$ lifetime is significantly shorter than that for $J = 2$ but no conclusions regarding additional decay channels were drawn by those authors.

We have also made theoretical calculations of the de-excitation probabilities of $2s3p\ ^3P$ in N IV, O V and F VI. In these calculations we included three even configurations, $2s^2$, $2p^2$ and $2s3s$ and two odd ones, $2s3p$ and $2p3s$. Hartree-Fock wavefunctions and parameter values were obtained with the Froese-Fischer computer program [35]. A computer program developed by Cowan [36] was then used to calculate and diagonalize the energy matrices and to determine theoretical transition probabilities for electric dipole radiation from the $2s3p$ and $2p3s$ to the low even levels. The energy parameters from the Hartree–Fock calculations were scaled to obtain a reasonable fit between observed and calculated level energies. Scaling factors between 0.6 and 1.0 were used. The low values used for the exchange parameters $G^0(2s, 3s)$, $G^1(2s, 3p)$ and $G^1(2p, 3s)$ indicate that further configuration interactions should be considered. Such an addition could change the eigenvector composition of the levels. However, in view of the good agreement between our transition

Table I. *Lifetimes of the $2s3p\ ^3P_{0,1,2}$ levels in N IV, O V and F VI*

Spectrum	Upper level	Wavelength (Å)	Experimental lifetime (ns)		Theoretical lifetime (ns)	
			This work	Other[a]	This work	Other[a,b]
N IV	$^3P_2$	3478.71	8.98 ± 0.10	9.65 ± 0.12[c]	8.2	8.82[f,g]; 7.40[h]; 7.89[i]
	$^3P_1$	3482.99	8.72 ± 0.12	9.74 ± 1.36[c]	7.9	9.19[j,g]
	$^3P_0$	3484.96		10.08 ± 0.57[c]	8.2	
O V	$^3P_2$	2781.01	5.36 ± 0.07	5.4 ± 0.2[d]; 4.8 ± 0.5[e]	5.2	6.42[f,g]; 4.86[h]; 4.77[i]
	$^3P_1$	2786.99	4.74 ± 0.07	4.8 ± 0.5[d]; 4.3 ± 0.4[e]	4.8	6.95[j,g]
	$^3P_0$	2789.85	5.26 ± 0.07		5.2	
F VI	$^3P_2$	2315.39	3.07 ± 0.04		3.4	5.57[j,g]
	$^3P_1$	2323.35	2.41 ± 0.04		2.4	
	$^3P_0$	2327.23	3.04 ± 0.04		3.4	

[a] This compilation is not complete, see discussions in the text.
[b] No J-dependent effects included. [c] Lewis et al. [27].
[d] Lewis et al. [28]. [e] Druetta et al. [29]. [f] Pfennig et al. [37]. [g] Upper limit (see text).
[h] Nussbaumer [2]. [i] Hummer and Norcross [39]. [j] Hibbert [38].

probabilities for $2s3s\ ^3S–2s3p\ ^3P$ and those based on more comprehensive calculations (see Table I) no larger calculations were attempted.

Our calculated lifetimes are compared in Table I with experimental and some selected theoretical values (for a complete bibliography see [13]). All previous calculations give multiplet strengths and do not consider J-dependent effects on the $2s3p\ ^3P$ lifetimes. The Hartree-Fock calculations of Pfennig et al. [37] and the C I calculations of Hibbert [38] only include the $2s3s\ ^3S–2s3p\ ^3P$ decay. Their lifetimes should thus be considered as upper limits. The multiconfiguration calculations of Nussbaumer [2] and Hummer and Norcross [39] also gave the f-values for the $2p^2\ ^3P–2s3p\ ^3P$ branch which is made possible by configuration interaction between $2s3p$ and $2p3s$. Those authors also predict that the ratio between transition probabilities $A(2p^2\ ^3P–2s3p\ ^3P)/A(2s3s\ ^3S–2s3p\ ^3P)$ is about 0.2 in N IV, 0.5 in O V and between 1 and 2 in Ne VII, F VI being not considered in [2, 39]. Our theoretical analyses show, not unexpectedly, that the $2p^2\ ^3P–2s3p\ ^3P$ transition probability is very sensitive to the number of configurations included in the calculations. A somewhat lower transition probability for this branch in O V than those in [2, 39] would result in better agreement with the experimental results obtained by us and by Lewis et al. [28]. The $2p^2\ ^3P_2–2s3p\ ^3P_2$ transition has been observed in O V [40] but its intensity was quite low.

From our experimental data in Table I we can directly determine the transition probability for the $2s^2\ ^1S_0–2s3p\ ^3P_1$ transition. We also determined the ratio between the decay curves for $J = 1$ and $J = 2$ levels (obtained under identical conditions). One such result, from point-by-point division of the experimental data, is shown in Fig. 5. The slope of the straight line, fitted to the data, gives us the $2s^2\ ^1S_0–2s3p\ ^3P_1$ transition probability.

Our experimental and theoretical results for the intercombination transition are summarized in Table II. The experimental data are very uncertain for N IV while the results are much more reliable for higher Z. The agreement between theory and experiment is quite satisfactory. The calculations show that other decay channels from $^3P_1$ to singlet levels, i.e., $2p^2\ ^1S_0$ and $^1D_2$ and $2s3s\ ^1S_0$ amount to less than 5% of that to $2s^2\ ^1S_0$. This indicates that the deviation of the experimental lifetime for $^3P_1$ from those for $^3P_0$ and $^3P_2$ is almost entirely caused by $2s^2\ ^1S_0–2s3p\ ^3P_1$. The $^3P_2$ level can also decay to $2p^2\ ^1D_2$ and by magnetic quadrupole (M2) transition to the $2s^2\ ^1S_0$ ground state. The good agreement between $^3P_0$ and $^3P_2$ lifetimes indicates that these branches are very weak, however. In our calculations we obtain the transition probability for $2p^2\ ^1D_2–2s3p\ ^3P_2$ to be less than $10^4\ \mathrm{s}^{-1}$. Lin et al. [41] have calculated the $2s^2\ ^1S_0–2s2p\ ^3P_2$ decay probabilities in the Be I sequence. In O V it is found to be more than 10^4 smaller than the $2s^2\ ^1S_0–2s2p\ ^3P_1$ transition probability. Similar ratios might be expected for the $2s3p\ ^3P_{0,1,2}$ decay.

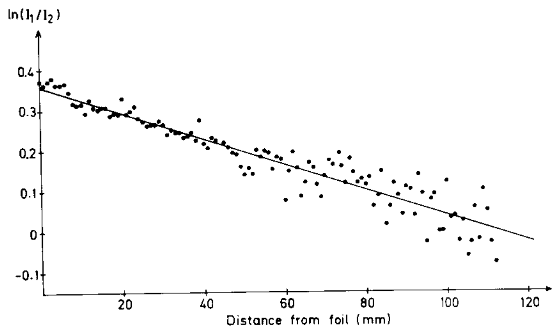

Fig. 5. Ratio between the decay curves for the $2s3p\ ^3P_1$ (labelled I_1) and $2s3p\ ^3P_2$ (labelled I_2) levels in O V. This ratio varies exponentially with the distance from the foil, the slope giving the probability for the intercombination transition $2s^2\ ^1S_0–2s3p\ ^3P_1$.

Table II. *Transition probabilities for the $2s^2\ ^1S_0–2s3p\ ^3P_1$ intercombination line in N IV, O V and F VI*

Spectrum	Wavelength (Å)[a]	Transition probability ($10^6\ \mathrm{s}^{-1}$) Experiment	Theory
N IV	247.20	3.3 ± 2.7	5
O V	171.57	22 ± 6	15
F VI	126.53	88 ± 9	120

[a] Calculated from known energy differences [16–18].

In view of the comparatively high transition probability for $2s^2\ ^1S_0–2s3p\ ^3P_1$ in N IV, O V and F VI it should clearly be worthwhile to search for these lines in laboratory and astrophysical spectra. In Table II we have included the wavelengths for these intercombination lines in N IV, O V and F VI, computed from known level energies [16–18]. In the very detailed oxygen spectra of Edlén [40] the spin–forbidden $2s^2\ ^1S_0–2s3p\ ^3P_1$ line in O V was probably obscured by an intense Li II transition ($1s^2\ ^1S–1s4p\ ^1P$) at 171.582 Å. A search for such intercombination lines could also be performed using the beam-foil method. Using a tandem Van de Graaff accelerator equipped with a sputtering ion source one could investigate the spectra of, e.g., Mg IX, Al X and Si XI in the grazing-incidence region, the main advantage being the purity of the spectra. From differential measurements on the $2s3p\ ^3P_{0,1,2}$ lifetimes in these ions it would also be possible to obtain additional information as to the probability of the intercombination transition.

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