

OSCILLATOR STRENGTHS FOR ULTRAVIOLET TRANSITIONS IN P II

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ABSTRACT

We report lifetimes, branching fractions, and the resulting oscillator strengths for transitions within the P II multiplet ($3s^2 3p^2 \ ^3P - 3s^2 3p 4s \ ^3P^o$) at 1154 Å. These beam-foil measurements represent the most comprehensive and precise set currently available experimentally. Comparison with earlier experimental and theoretical results is very good. Since Morton's most recent compilation is based on the earlier body of results, phosphorus abundances for interstellar material in our Galaxy and beyond derived from $\lambda 1154$ do not require any revision.

Subject headings: atomic data — ISM: abundances — ISM: atoms — methods: laboratory — ultraviolet: ISM

1. INTRODUCTION

Singly ionized phosphorus is the dominant form of this element in the neutral interstellar medium. Most astronomical studies rely on the $^3P_0 - ^3P_1$ transition at 1153 Å, because it is one of the strongest in P II and is in a relatively clean portion of the spectrum. For instance, observations of diffuse clouds in the Galaxy (Dufton et al. 1986; Jenkins et al. 1986) and in the Small Magellanic Cloud (Mallouris et al. 2001) focused on the amount of phosphorus depleted onto the surface of interstellar grains. In more distant galaxies and damped Ly α systems, P II absorption then reveals the metallicity of the gas and the system's nucleosynthetic history (e.g., Molaro et al. 2001; Levshakov et al. 2002; Pettini et al. 2002). Here we present the most comprehensive and precise experimental results to date for all transitions within the multiplet associated with the line $\lambda 1153$.

The above astronomical studies use oscillator strengths (f -values) compiled by Morton (1991, 2003) from the theoretical computations of Hibbert (1988) and experimental lifetime of Livingston et al. (1975). Hibbert's results represent an improvement over his earlier calculation (Hibbert 1986), which did not include the $3s^2 3p 4p$ states. Other work on the $3s^2 3p^2 \ ^3P - 3s^2 3p 4s \ ^3P^o$ multiplet includes an experiment (Smith 1978) and computational efforts (Brage et al. 1993; Tayal 2003; Froese Fischer et al. 2006). Our beam-foil measurements on lifetimes and branching fractions allow us to derive the first purely experimental f -values for comparison with theory. Our results are presented and then discussed after we describe the experiment.

2. EXPERIMENTAL DETAILS

The beam-foil measurements were performed at the Toledo Heavy Ion Accelerator. Details about the facility and general aspects of the experimental procedures can be found in our earlier papers (e.g., Federman et al. 1992; Haar et al. 1993; Schectman et al. 2000). Here we focus on the particulars for the P II data. Phosphorus ions were produced by heating red phosphorus in a low-temperature oven and by subsequent charging through interactions in an Ar plasma. Most lifetime measurements and the spectra for branching fractions were obtained at an energy of 170 keV. Systematic effects, such as beam divergence, foil thickening, and nuclear scattering, were studied

through comparisons of forward and reverse decay curves and of data acquired at 240 keV. Typical P⁺ beam currents were 200 nA. The ions emerged in a variety of charge states and excited states on passage through carbon foils whose thicknesses were 2.4 $\mu\text{g cm}^{-2}$. An Acton 1 m normal-incidence vacuum ultraviolet monochromator with a 2400 line mm^{-1} grating blazed at 800 Å was used for the transitions involving the multiplet at 1154 Å. The radiation was detected with a Galileo channeltron electron multiplier. Cascades that could repopulate the upper states of interest with wavelengths in the visible portion of the spectrum were sought with a 600 line mm^{-1} grating blazed at 3000 Å and an S20 photomultiplier (Centronic Q4283) cooled with dry ice.

Lifetimes for the three values of J in the upper fine-structure levels of the multiplet $\lambda 1154$ were obtained from decay curves for all transitions between $3p^2 \ ^3P$ and $3p 4s \ ^3P^o$. The lifetimes were extracted from multiexponent fits. The decay curves were best fit by two exponentials; we ascribe the weaker and longer lived decay to a cascading transition that repopulates the upper level of interest. Figure 1 shows the decay curve for the $^3P_2 - ^3P_2^o$ line at 1154 Å. The presence of the second decay necessitated our acquiring measurements on all six transitions within the multiplet for the derivation of accurate branching fractions. This yielded more precise determinations for the primary decay from the upper levels with $J = 1$ and 2.

A search for the transitions at visible wavelengths that were responsible for repopulating $^3P^o$ was conducted. The purpose was to obtain an independent measure of the lifetime in order to perform the method of arbitrarily normalized decay curves (ANDC) (see Curtis et al. 1971). The ANDC method leads to a more secure value for the lifetime of the primary decay of most interest to the current study. Our measurements revealed a lifetime for the secondary decay of about 10 ns. Large-scale computations (Hibbert 1988; Tayal 2003; Froese Fischer et al. 2006) suggest that transitions originating from $3p 4p \ ^3D$ cause the repopulation. The lines occur around 6000 Å but were too weak to enable us to carry out the analysis.

Branching fractions are needed to convert lifetimes into oscillator strengths when more than one channel for decay is present. Theoretical (Hibbert 1988; Tayal 2003; Froese Fischer et al. 2006) and semiempirical (Curtis 2000) calculations indicate that intercombination lines arising from the $3p 4s \ ^3P^o$ state are

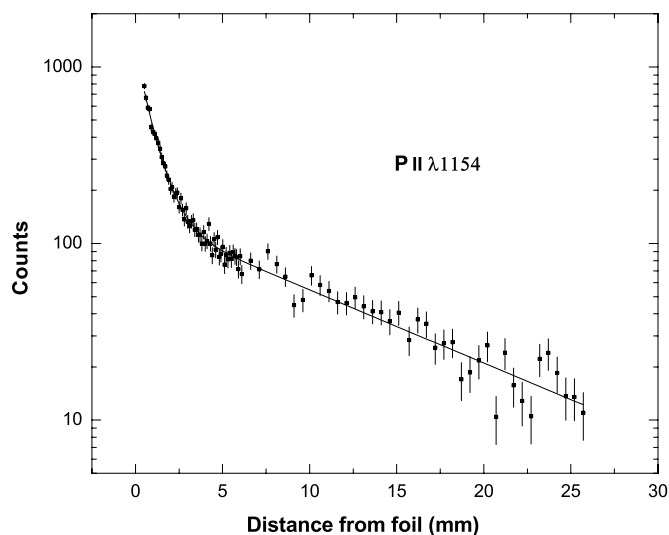


FIG. 1.—Measured P II decay curve for the line at 1154 Å for a beam energy of 170 keV. The postfoil beam velocity at this energy was $1.0068 \text{ mm ns}^{-1}$, thus establishing the time since excitation for a given foil position. The foil was moved relative to the monochromator entrance slit in increments of 0.1 mm until it was displaced 5 mm; then the increments were increased to 0.5 mm. A two-exponential fit to the data is shown by the solid curve.

weak (branching fractions less than 2%, which are below the sensitivity of our experiment). As a result, we focused on branching among the dipole-allowed transitions between 1150 and 1160 Å; the scan revealing these transitions, from which branching fractions were obtained, appears in Figure 2. This was accomplished by determining the relative integrated intensities from lines with a common upper level through Gaussian fits. Since the fits indicated line widths that were indistinguishable from one another, we relied on the intensities, after correcting for the contribution (about 10%) from the secondary decay noted above. Because the spectral interval is small, systematic differences in instrumental response are not discernible with our sensitivity. This point is addressed further below.

3. RESULTS AND DISCUSSION

The results of our lifetime measurements appear in Table 1, and the oscillator strengths derived from our branching frac-

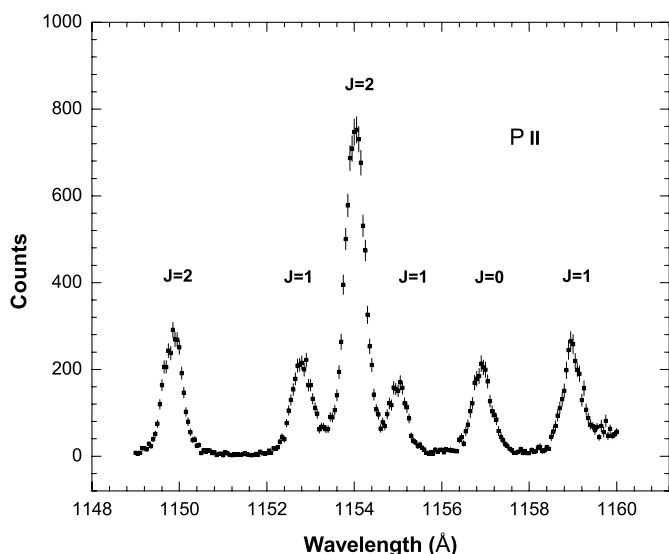


FIG. 2.—Spectrum of the P II multiplet at 1154 Å. The total angular momentum quantum number for each upper fine-structure level is indicated.

TABLE 1
P II LIFETIMES FOR $3s^23p4s^3P^o$ LEVELS

J_u	τ (ns)						
	Present	LKIP ^a	S ^b	H ^c	BMF ^d	T ^e	FTI ^f
0.....	0.79 ± 0.10	...	...	0.82	...	0.784	0.796
1.....	0.79 ± 0.06	...	...	0.81	...	0.778	0.789
2.....	0.84 ± 0.07	0.85 ± 0.11	1.3 ± 0.5	0.80	0.80	0.772	0.776

^a Livingston et al. (1975); beam-foil experiment.

^b Smith (1978); phase shift experiment.

^c Hibbert (1988); configuration interaction calculation.

^d Brage et al. (1993); multiconfiguration Hartree-Fock calculation.

^e Tayal (2003); multiconfiguration Hartree-Fock calculation.

^f Froese Fischer et al. (2006); multiconfiguration Hartree-Fock calculation.

tions are given in Table 2. The tables also provide comparisons with earlier experimental (Livingston et al. 1975; Smith 1978) and theoretical work (Hibbert 1988; Brage et al. 1993; Tayal 2003; Froese Fischer et al. 2006). The preferred f -values from the most recent compilation of Morton (2003), which are based on the work of Livingston et al. and Hibbert, are included in Table 2. The experimentally determined branching fractions used to transform the lifetimes for the $J_u = 1$ level into f -values are 0.359 ± 0.027 ($J_l = 0$), 0.254 ± 0.014 ($J_l = 1$), and 0.387 ± 0.026 ($J_l = 2$). The corresponding values for the $J_u = 2$ level are 0.267 ± 0.016 ($J_l = 1$) and 0.733 ± 0.033 ($J_l = 2$). Our branching fractions agree very well with those derived from theoretical and semiempirical analyses (Hibbert 1988; Brage et al. 1993; Curtis 2000; Tayal 2003; Froese Fischer et al. 2006), as can be inferred from the comparison in Table 2.

The agreement between our results for lifetimes and f -values and others is very good. Although our determinations are the most precise ones currently available experimentally, the agreement with theory has not suffered. This is not unexpected, since the intercombination lines involving $3p4s^3P^o$ as the upper state are quite weak, and there is little configuration interaction (CI) involving the upper or lower levels of the multiplet. On the other hand, CI is much more prominent in other P II multiplets, including $\lambda\lambda 964, 967$, and 1308 (respectively, $3s^23p^2^3P-3s^23p3d^3D^o$, $3s^23p3d^3P^o$, and $3s3p^3^3P^o$), and the agreement among theoretical calculations is much worse. Since astronomical studies make use of transitions in these three multiplets, we plan future measurements in an attempt to resolve the discrepancies now present.

We also were able to obtain the lifetime for each upper fine-structure level and branching fractions for all transitions within the multiplet. Thus, our measurements are the most comprehensive to date. This set of data can be used to test the hypothesis (e.g., Curtis 2000) that in cases where there is little CI, semiempirically derived branching fractions can provide a means to help calibrate instruments below 2000 Å. This will be discussed further elsewhere.

4. CONCLUSIONS

We presented beam-foil measurements on lifetimes and branching fractions for the multiplet at 1154 Å in P II. These were combined to yield f -values that are needed for studies of interstellar abundances and the history of nucleosynthesis from quasar absorption-line systems. The measurements represent the most comprehensive and precise set available experimentally for the multiplet. The lifetimes and oscillator strengths agree very well with earlier determinations and the Morton (2003)

TABLE 2
P II OSCILLATOR STRENGTHS FOR THE MULTIPLY $3s^2 3p^2 \ ^3P-3s^2 3p4s \ ^3P^o$

λ_{ul} (Å)	J_l	J_u	f -Value ($\times 10^{-2}$)							
			Present	LKIP ^a	S ^b	H ^c	BMF ^d	T ^e	FTI ^f	M ^g
1149.958.....	1	2	10.5 ± 1.1	...	...	10.4 ^h	...	10.8 ^h	10.8	10.4
	...	...	...	...	...	11.3 ⁱ	...	10.4 ⁱ	...	...
1152.818.....	0	1	27.2 ± 2.9	...	...	24.4 ^h	...	25.1 ^h	25.3	24.5
	...	...	...	...	...	26.4 ⁱ	...	24.1 ⁱ	...	...
1153.995.....	2	2	17.4 ± 1.6	...	...	18.6 ^h	...	19.2 ^h	19.3	18.6
	...	...	...	...	...	20.1 ⁱ	...	18.4 ⁱ	...	...
1155.014.....	1	1	6.4 ± 0.6	...	...	6.1 ^h	...	6.2 ^h	6.3	6.1
	...	...	...	...	...	6.5 ⁱ	...	6.0 ⁱ	...	...
1156.970.....	1	0	8.5 ± 1.1	...	...	8.1 ^h	...	8.5 ^h	8.4	8.2
	...	...	...	...	...	8.8 ⁱ	...	8.1 ⁱ	...	...
1159.086.....	2	1	5.9 ± 0.6	...	...	6.2 ^h	...	6.3 ^h	6.3	6.2
	...	...	...	...	...	6.7 ⁱ	...	6.0 ⁱ	...	...
Multiplet.....	...	...	24.4 ± 1.2	23 ± 3	15.0	24.7 ^h	25.2 ^h	...	...	24.7
	...	...	...	...	...	26.7 ⁱ	25.0 ⁱ	...	...	...

^a Livingston et al. 1975.

^b Smith 1978.

^c Hibbert 1988.

^d Brage et al. 1993.

^e Tayal 2003.

^f Froese Fischer et al. 2006.

^g Morton (2003) compilation.

^h Based on length formalism.

ⁱ Based on velocity formalism.

compilation. Since the intercombination lines arising from the upper levels in the multiplet are weak, and since there is little configuration interaction, the close agreement is not unanticipated. There are transitions in other multiplets (at 964, 967, and 1308 Å) that are used in the astronomical studies. Configuration interaction is much stronger for these three multiplets, and the available results differ significantly; we plan future measurements to help resolve the discrepancies. Then phosphorus abundances

based on any of the well-studied ultraviolet lines will be known more securely.

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