Oscillator Strengths for Ultraviolet Transitions in P II – The Multiplet at 1308 Å

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ABSTRACT

We report lifetimes, branching fractions, and the resulting oscillator strengths for transitions within the P II multiplet ($3s^23p^2\ ^3P - 3s3p^3\ ^3P^o$) at 1308 Å. These comprehensive beam-foil measurements, which are the most precise set currently available experimentally, resolve discrepancies involving earlier experimental and theoretical results. Interstellar phosphorus abundances derived from λ1308 can now be interpreted with greater confidence. In the course of our measurements, we also obtained an experimental lifetime for the $3p4s\ ^3P^o_0$ level of P IV. It agrees well with the available theoretical calculation.

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

1. Introduction

Singly-ionized phosphorus, which is the element's dominant charge state in neutral diffuse interstellar gas, is used to probe depletion onto interstellar grains in the Galaxy (Dufton, Keenan, & Hibbert 1986; Jenkins, Savage, & Spitzer 1986; Lebouteiller, Kuassivi, & Ferlet 2005; Cartledge et al. 2006) and in the Small Magellanic Cloud (Mallouris et al. 2001). Knowledge of the amount of depletion in terms of gas density then allows studies of metallicity and nucleosynthetic history in more distant galaxies and damped Lyman-α systems (e.g., Molaro et al. 2001; Levshakov et al. 2002; Pettini et al. 2002) via P II absorption.

Two transitions originating from the ground state ($\lambda\lambda$1153,1302) are the most commonly used ones for Galactic studies (e.g., Jenkins et al. 1986; Cartledge et al. 2006). These transitions have moderate to moderately large oscillator strengths or f-values, as noted in the most recent compilation of Morton (2003); the line at 1301 Å is the weaker of the two. Morton recommended the theoretical f-values of Hibbert (1988) for the multiplet (λ1308) containing the line at 1301 Å. Hibbert's computed lifetimes for the upper levels $3s3p^3\ {}^3P^{\rm o}_j$ are in close agreement with the experimental results of Livingston et al. (1975), who quoted about 20% accuracy. Other experimental results (Savage and Lawrence 1966; Curtis, Berry, & Bromander 1971; Smith 1978) for this multiplet, however, differ considerably (factors of 2) from those of Livingston et al. The early theoretical work of Beck & Sinanoğlu (1972) agreed reasonably well with the experimental results available at the time (Savage & Lawrence 1966; Curtis et al. 1971). The theoretical results of Brage, Merkelis, & Froese Fischer (1993) lie between those of Curtis et al. (1971) and Livingston et al. (1975). More recent large-scale calculations do not provide a resolution. While the results of Tayal (2003) and Froese Fischer, Tachiev, & Irimia (2006) agree very well, the f-values are nearly twice those given by Hibbert (1988).

These conflicting results have forced astronomers to derive empirical f-values from interstellar spectra, but the situation remains unsatisfactory. Based on their comparison of b-values for interstellar S II and P II lines, Harris & Mas Hesse (1986) suggested a value of 9.2 for the ratio of f-values for the lines at 1153 and 1302 Å. Dufton et al. (1986), on the other hand, adopted earlier calculations by Hibbert (1986) and analyzed their data with a ratio of 22, which is similar to the ratio from Hibbert (1988). For comparison, Brage et al. (1993) obtained a ratio of 11.2, Tayal (2003) a ratio of 11.5, and Froese Fischer et al. (2006) a ratio of 12.1.

We seek a resolution to the question of the most appropriate f-values to use for interstellar studies by extending our earlier results on the multiplet containing the line at 1154 Å (Federman et al. 2007) through measurements of the pertinent data for the multiplet λ1308. We present experimental lifetimes and branching fractions, from which f-values are derived, through the use of beam-foil spectroscopic techniques. Our empirical results are the most comprehensive to date and are of sufficient accuracy to discern the most consistent theoretical efforts.

2. Experimental Details

The measurements were performed at the Toledo Heavy Ion Accelerator. Details 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 specfics relevant to the P II data for the multiplet at λ1308. As in our earlier work on P II (Federman et al. 2007), phosphorus ions were produced by in a low-temperature oven and by subsequent charging through interactions in an Ar plasma. Lifetime measurements and the spectra for branching fractions were obtained at energies of 170 and 240 keV. Beam divergence, foil thickening, and nuclear scattering were investigated (see Federman et al. 2007). Typical P^+ beam currents were 200 nA. The ions passed through carbon foils whose thicknesses were 2.4 μg cm^{-2} and emerged in a variety of charge states and excited states. An Acton 1 m normal-incidence vacuum ultraviolet monochromator with a 2400 line mm^{-1} grating blazed at 800 Å was used for all the measurements. A Galileo channeltron electron multiplier detected the emitted radiation.

Blending among spectral features and the relative weakness of the lines of interest prevented us from performing a complete set of measurements. We instead focused on those that would yield secure results. Lifetimes for the $J = 1$ and 2 levels in the upper state $3s3p^3$ $^3P^{\mathrm{o}}$ were obtained from decay curves involving transitions at 1301 and 1310 Å, respectively, to the ground state $3p^2$ ^3P. Systematic effects were studied by the acquisition of decay curves for $J = 2$ at two energies. Multiexponential fits were used to extract lifetimes. However, in most instances a single exponential sufficed. The decay curve for $J = 2$ obtained in the forward direction (i.e., moving away from the slit of the monochromator) was best fit by two exponentials; we ascribe the short-lived decay to a transition in P IV at 655 Å seen in second order ($3p^2$ $^3P_1$ – $3p4s$ $^3P^{\mathrm{o}}_0$). We only saw the effects of P IV in one decay curve because the feature is present on the red side of the P II line and therefore depended on the placement of the grating when peaking up on λ1310. Additional measurements at 240 keV were made on the P IV line at 655 Å for further confirmation. Figure 1 shows the decay curve for the $^3P_2 - {}^3P^{\mathrm{o}}_2$ line of P II at 1310 Å.

Cascades from higher lying levels, which affect the populations of the levels of interest, could impact our lifetime measurements. Large-scale computations (Hibbert 1988; Tayal 2003; Froese Fischer et al. 2006), however, suggest that repopulation is not a concern in our experiment. These calculations indicate that decays from the $3s^2 3p4p$ ^3D, ^3P, and ^3S states may repopulate the $3s3p^3$ $^3P^{\mathrm{o}}$ state, with typical lifetimes of 7 to 12 ns. We do not find lifetimes in this range from our multiexponential fits. More importantly, Hibbert (1988) and Froese Fischer et al. (2006) determined multiplet Einstein A coefficents for transitions between these states that were less than a few times 10^7 s^{-1}; these transitions are too weak to play a significant role in repopulation.

When more than one decay channel is present, a combination of lifetimes and branching fractions are needed to derive oscillator strengths. The theoretical results of Hibbert (1988), Tayal (2003), and Froese Fischer et al. (2006) indicate that intercombination lines arising from the $3s3p^3$ $^3P^{\mathrm{o}}$ state are weak and are below the sensitivity of our experiment. Therefore, we focused on branching among the dipole-allowed transitions between 1300 and 1312 Å.

Two scans were required to cover the multiplet, overlapping in the region between 1304 and 1306 Å. The two halves of the spectrum taken at 240 keV were scaled by the intensity of the blend of P II lines in this region. The added signal in this portion of the spectrum aided in fitting the blend of lines. A further complication was the numerous weak lines from P IV seen in second order at these wavelengths. Guided by the measurements on P IV $\lambda 655$, the spectral scan was acquired 4 mm upstream of the monochromator entrance slit, thereby assuring us that the remaining intensities were the result of P II lines of interest. The spectrum appears in Fig. 2. Branching fractions are usually determined by measuring the relative integrated intensities from lines with a common upper level through Gaussian fits. The fitting proceedure indicated that the line widths were indistinguishable from one another; we, therefore, relied on the intensities. The spectral interval is small enough that systematic differences in instrumental response are not a concern.

3. Results and Discussion

Tables 1 and 2 show the results of our lifetime measurements and the oscillator strengths derived from our branching fractions. The tables also provide comparisons with earlier experiments (Savage & Lawrence 1966; Curtis et al. 1971; Livingston et al. 1975; Smith 1978) and theoretical calculations (Beck & Sinanoğlu 1972; Hibbert 1988; Brage et al. 1993; Tayal 2003; Froese Fischer et al. 2006). Morton's (2003) recommended f-values, which are based on the work of Livingston et al. and Hibbert, are are also shown in Table 2.

Our lifetime measurements are most consistent with the beam-foil results of Livingston et al. (1975) and with the theoretical calculations of Brage et al. (1993), Tayal (2003), and Froese Fischer et al. (2006). These theoretical efforts were based on versions of the multiconfiguration-Hartree-Fock (MCHF) technique, with corrections for relativistic effects. Our lifetime for the $3p4s\ {}^3P_0^{\mathrm{o}}$ level of P IV is 0.27 ± 0.04 ns, a value that agrees with the theoretical prediction of Gupta & Msezane (2002) (0.2205 ns); they used the CIV3 code of Hibbert (1975). The isolated measurement confirms our supposition that the short-lived decay found for the $J = 2$ level of P II $3s3p^3\ {}^3P^{\mathrm{o}}$ (see Fig. 1) arises from P IV. The result for P IV leads us to the following suggestions regarding earlier experimental determinations. First, the shorter lifetime obtained by Curtis et al. (1971), also based on beam-foil spectroscopy, could be the result of contamination from the P IV decay. Second, Livingston et al. (1975) noted the presence of a second decay besides the one associated with P II with a lifetime of 1.2 ± 0.4 that they ascribed to a blend with O I. Within the precision of their measurements, the shorter lifetime could instead arise from P IV.

Hibbert (1988), Tayal (2003), and Froese Fischer et al. (23006) provided a complete set of results for the multiplet at 1308 Å, from which branching fractions can be inferred. The branching fractions from the three calculations agree well and show slight differences from those obtained from LS coupling rules. For $J_u = 2$, LS coupling gives relative strengths of 0.750 and 0.250 for the transitions to $J_l = 2$ and $J_l = 1$. Hibbert (1988), Tayal (2003), and Froese Fischer et al. (2009) each found branching fractions of 0.76 and 0.24. Some minor variation was found among the theoretical calculations for the $J_u = 1$ branching fractions, where LS coupling gives 0.417, 0.250, and 0.333 for decays to $J_l = 2$, 1, and 0. Hibbert (1988) obtained respective values of 0.38, 0.27, and 0.35, while those of Tayal (2003) are 0.39, 0.27, and 0.34 and those of Froese Fischer et al. (2006) are 0.41, 0.25, and 0.33.

Although the three computations yielded very similar branching fractions, we obtained experimental values to check for the possibility of unexpected anomalies. The results from fitting our spectrum to the multiplet are consistent with these predictions, but they do not favor one over another because the experimental uncertainties are too large. The experimentally determined branching fractions for the $J_u = 2$ level are $xxx \pm 0.0$ ($J_l = 1$) and $yyy \pm 0.0$ ($J_l = 2$), while for the $J_u = 1$ level they are $aaa \pm 0.0$ ($J_l = 0$), $bbb \pm 0.0$ ($J_l = 1$), and $ccc \pm 0.0$ ($J_l = 2$).

4. Conclusions

Results of beam-foil measurements yielding lifetimes and branching fractions for the P II multiplet at 1308 Å were presented. These were combined to yield f-values that are needed for studies of the phosphorus abundance in the diffuse interstellar medium of our Galaxy and more distant ones.

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Table 1. P II Lifetimes for $3s3p^3\ ^3P^{\rm o}$ Levels

J_u	τ (ns)								
	Present	SL[a]	CMB[b]	LKIP[c]	S[d]	H[e]	BMF[f]	T[g]	FTI[h]
1	14.0 ± 0.8	6.4 ± 0.8	9.0 ± 0.5	15 ± 4	5.4 ± 0.6	20.7	...	12.5	12.2
2	14.6 ± 0.5	6.4 ± 0.8	9.0 ± 0.5	15 ± 4	5.4 ± 0.6	22.6	12.3	13.4	13.0

[a] Savage & Lawrence 1966 – phase shift experiment.

[b] Curtis et al. 1971 – beam-foil experiment.

[c] Livingston et al. 1975 – beam-foil experiment.

[d] Smith 1978 – phase shift experiment.

[e] Hibbert 1988 – configuration interaction calculation.

[f] Brage et al. 1993 – multi-configuration Hartree-Fock calculation.

[g] Tayal 2003 – multi-configuration Hartree-Fock calculation.

[g] Froese Fischer et al. 2006 – multi-configuration Hartree-Fock calculation.

Table 2. P II Oscillator Strengths for the Multiplet $3s^23p^2\ ^3P - 3s3p^3\ ^3P^o$

λ_{ul} (Å)	J_l	J_u	f-value ($\times 10^{-3}$)										
			Present	SL[a]	CMB[b]	BS[c]	LKIP[d]	S[e]	H[f]	BMF[g]	T[h]	FTI[i]	M[j]
1310.70	2	2	±	...	...	...	...	...	8.4[k]	...	14.6[k]	15.1	8.4
	...	...	...	...	...	...	...	...	8.0[l]	...	14.6[l]	...	...
1309.87	2	1	±	...	...	...	...	...	2.8[k]	...	4.8[k]	5.3	2.8
	...	...	...	...	...	...	...	...	2.6[l]	...	4.8[l]	...	...
1305.50	1	2	±	...	...	...	...	...	4.5[k]	...	7.6[k]	8.1	4.5
	...	...	...	...	...	...	...	...	4.5[l]	...	7.7[l]	...	...
1304.68	1	1	±	...	...	...	...	...	3.4[k]	...	5.5[k]	5.4	3.4
	...	...	...	...	...	...	...	...	3.3[l]	...	5.6[l]	...	...
1304.49	1	0	±	...	...	...	...	...	4.5[k]	...	7.0[k]	7.2	4.5
	...	...	...	...	...	...	...	...	4.4[l]	...	7.0[l]	...	...
1301.87	0	1	±	...	...	...	...	...	12.7[k]	...	20.7[k]	21.0	12.7
	...	...	...	...	...	...	...	...	12.6[l]	...	21.0[l]	...	...
Multiplet	...	...	±	40 ± 5	29 ± 2	38.2[k]	17 ± 5	48	11.8[k]	22.6[k]	...	...	11.8
	...	...	...	...	...	43.6[l]	...	...	11.4[l]	23.0[l]	...	...	...

[a] Savage & Lawrence 1966.

[b] Curtis et al. 1971.

[c] Beck & Sinanoğlu 1972 – nonclosed many-electron theory.

[d] Livingston et al. 1975.

[e] Smith 1978.

[f] Hibbert 1988.

[g] Brage et al. 1993.

[h] Tayal 2003.

[i] Froese Fischer et al. 2006.

[j] Morton 2003 compilation.

[k] Based on length formalism.

[l] Based on velocity formalism.

Fig. 1.— The measured P II decay curve for the line at 1154 Å for a beam energy of 170 keV. The post-foil beam velocity at this energy was 1.0068 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.

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