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## Lifetimes and Oscillator Strengths for Ultraviolet Transitions in P II, Cl II and Cl III

S. Cheng, S. R. Federman, R. M. Schectman, M. Brown, & R. E. Irving

*Department of Physics and Astronomy, University of Toledo, Toledo, OH 43606*

scheng@physics.utoledo.edu, steven.federman@utoledo.edu,  
rms@physics.utoledo.edu, mbrown@physics.utoledo.edu,  
rirving@physics.utoledo.edu

M. C. Fritts

*School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455*

fritts@physics.umn.edu

N. D. Gibson

*Department of Physics and Astronomy, Denison University, Granville, OH 43023*

gibson@denison.edu

### ABSTRACT

Oscillator strengths for transitions in P II, Cl II and Cl III are derived from lifetimes and branching fractions measured with beam-foil techniques. The focus is on the multiplets with a prominent interstellar line at 1153 Å in P II which is seen in spectra of hot stars, and the lines at 1071 Å in Cl II and 1011 Å in Cl III whose lines are seen in spectra of diffuse interstellar clouds and the Io torus acquired with the *Far Ultraviolet Spectroscopic Explorer*. These data represent the first complete set of experimental  $f$ -values for the lines in the multiplets. Our results for P II  $\lambda$ 1153 agree well with Curtis' semi-empirical predictions, as well as the large scale computations by Hibbert and by Tayal. The data for Cl II  $\lambda$ 1071 also agree very well with the most recent theoretical effort and with Morton's newest recommendations. For Cl III, however, our  $f$ -values are significantly larger than those given by Morton; instead, they are more consistent with recent large-scale theoretical calculations. Extensive tests provide confirmation that  $LS$  coupling rules apply to the transitions for the multiplets in Cl II and Cl III.

## 1. Introduction and Experiments

The analysis of atomic abundances in astronomical environments needs accurate oscillator strengths and lifetimes for the species involved. As an example, a prominent interstellar line at 1153 Å seen in spectra of hot stars arises from absorption in P II. Analysis of this line is used to derive phosphorus abundances and the  $f$ -value for  $\lambda 1302$  (e.g., Harris and Mas Hesse 1986). Another example for such a need is the precision oscillator strengths and lifetimes for Cl II and Cl III which are needed to infer the total Cl abundance in Io’s torus as observed by *FUSE* (Feldman et al. 2001, 2004). We present beam-foil measurements that produce relevant atomic data for those lines in P II, Cl II and Cl III.

The experiments were carried out by the beam-foil technique. Phosphorous or chlorine ions were accelerated to energies of 170 keV or 220 keV, passed through carbon foils with typical thicknesses of 2.2 – 2.5  $\mu\text{g cm}^{-2}$ , and emerged in a variety of charge states and excited states. The desired transitions were selected by a monochromator with suitable gratings and focused onto a channeltron detector. Various measurements were performed to account for systematic effects such as beam divergence, foil thickening, and nuclear scattering. The stability of the ion beam was monitored by a Faraday cup and by an optical monitor. Decay curves were obtained for each value of  $j$  in the upper fine-structure levels associated with the multiplet at 1154 Å in P II, 1071 Å in Cl II, and 1011 Å in Cl III. When an upper level has more than one channel for decay, branching fractions were measured to convert lifetimes into oscillator strengths. A spectrum of the P II multiplet at 1154 Å is shown in Figure 1.

## 2. Results and Discussion

(a) *Lifetimes:* The lifetimes for the P II upper states in the multiplet ( $3s^23p^2\ ^3P - 3s^23p4s\ ^3P^o$ ) are about 0.80 ns. This agrees with previous experimental results (Livingston et al. 1975) and theoretical results (Hibbert 1988). Our lifetimes for the Cl II multiplet  $\lambda 1071$  ( $3s^23p^4\ ^3P - 3s3p^5\ ^3P^o$ ) are about 9.0 ns, agreeing with previous experimental results (Lawrence 1969, Bashkin & Martinson 1971) and theoretical calculations (Tayal 2004). The lifetime for the Cl III multiplet  $\lambda 1011$  ( $3s^23p^3\ ^4S^o - 3s3p^4\ ^4P$ ) is found to be about 8.0 ns. This result, averaged from those of three decay channels that agree nicely with each other, is about 20% shorter than the result of Bashkin & Martinson (1971), but agrees much better with theoretical lifetimes of Huang (1984).

(b) *Branching Fractions:* The branching fractions for a given level for allowed transitions can be derived from the multiplet spectrum, such as that shown in Figure 1. Care was taken in extracting the fractions when transitions blend and when there was possible contamination from transitions from higher charge states. The branching fractions for the P II multiplet are given in Table 1, together with comparisons from three theoretical calculations. Our results agree well with Curtis’ (2000) semi-empirical predictions, as well as with

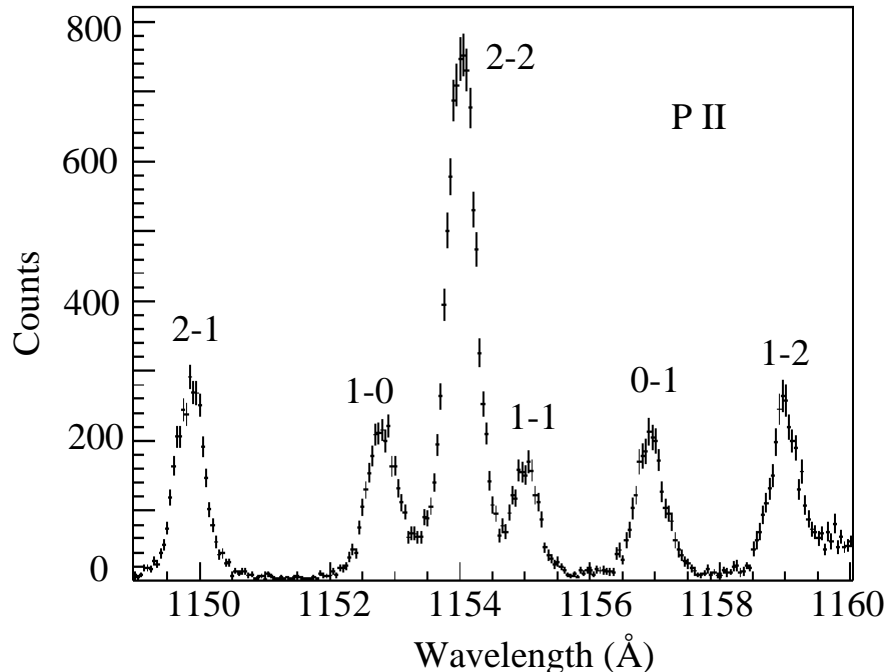


Fig. 1.— Spectrum of P II multiplet at 1154 Å. The  $j$ -values involved in the transitions have been labeled accordingly.

the large-scale theoretical computations by Hibbert (1988) and Tayal (2003). A comparison of P II branching fractions with classical  $LS$  coupling rules reveals that they are very similar. This implies that the P II multiplet is rather free of configuration interaction.

*(c) Oscillator Strengths:* From the measured lifetimes and branching fractions, we derived oscillator strengths for Cl II and Cl III, and the tabulated results can be found in Schectman et. al. (2005). Our results for Cl II are in excellent agreement with the extensive Hartree-Fock calculation of Tayal (2004) and with the recommendations of Morton (2003). Thus, there is no need to revise interstellar Cl II abundances obtained previously that are based on these recommendations. Our results for Cl III are consistent with most recent theoretical efforts (e. g., Huang 1984, Ho & Henry 1987). On the other hand, the correspondence with the measurement of Bashkin & Martinson (1971) and the calculations of Aymar (1973) is poor. Since Morton’s (2003) recommended  $f$ -values are based on the results from Bashkin & Martinson, they are about 30% smaller than those derived from our lifetimes and from most theoretical calculations.

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Table 1: Branching Fractions for P II ( $3s^23p^2\ ^3P$ -  $3s^23p4s\ ^3P^o$ ).

Transition	Present	<i>LS</i>	Hibbert (1988)	Curtis (2000)	Tayal (2003)
$\lambda 1153\ (^3P_0 - ^3P_1^o)$	$36.0 \pm 2.3$	33.3	33.1	33.1	32.8
$\lambda 1155\ (^3P_1 - ^3P_1^o)$	$25.3 \pm 1.7$	25.0	24.6	24.5	24.3
$\lambda 1159\ (^3P_2 - ^3P_1^o)$	$38.7 \pm 2.8$	41.7	41.4	41.0	40.9
$\lambda 1150\ (^3P_1 - ^3P_2^o)$	$26.6 \pm 1.6$	25.0	25.3	25.2	25.3
$\lambda 1154\ (^3P_2 - ^3P_2^o)$	$73.4 \pm 3.3$	75.0	74.7	74.8	74.7

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