Journal of Physics: Conference Series **130** (2008) 012007 doi:10.1088/1742-6596/130/1/012007

Oscillator strengths for ultraviolet transitions in P II and Cu II

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Abstract. Analysis of ultraviolet absorption from the dominant ions in interstellar clouds provides information on the mineralogy of the solid material in space and on the synthesis of elements in our Galaxy and beyond. For the most part the spectra are acquired with the spectrometers on the *Hubble Space Telescope* and the *Far Ultraviolet Spectroscopic Explorer*. In order to convert the amount of absorption into an accurate abundance, determinations of oscillator strengths of sufficiently high quality are needed. We present our most recent beam-foil measurements in this area. Lifetimes, branching fractions, and oscillator strengths for all transitions within the P II multiplet at 1154 Å are compared with available results. Close agreement between our laboratory measurements and theoretical and semi-empirical calculations suggests a means for calibrating fast-beam instruments in the far ultraviolet. As for Cu II, our results for the line at 1358 Å provide further evidence for a short lifetime for the upper state of interest.

1. Background

The main goal of our laboratory measurements is to provide the basis for more secure abundances of atoms and molecules in interstellar clouds, which are the sites for star and planet formation. Here we focus on recent work on ultraviolet lines seen in the spectra of P II and Cu II, which are the dominant ions in neutral interstellar clouds for the two elements. P II observations in our Galaxy and the Small Magellanic Cloud [1-4] focused on the amount of phosphorus depleted onto interstellar grains, while in more distant galaxies and Lyα systems, P II absorption reveals the metallicity and nucleosynthetic history (e.g., [5-7]). Ref. [4] also used Cu II measurements to study this element's incorporation into grains. The abundances depend on the adopted oscillator strengths, or *f*-values, and the precision with which they are known.

Our determination of the required *f*-values involves beam-foil spectroscopy, where lifetimes and branching ratios are obtained. We restrict ourselves to transitions where: (1) all known cascades have much greater lifetimes than that of the primary transition, or (2) a small number of observable cascades have lifetimes comparable to the one of primary interest. We then study these cascades using the ANDC (Arbitrarily Normalized Decay Curve) method [8]. We also consider a number of consistency checks. We monitor beam current with a Faraday cup and light output with an optical monitor simultaneously. Decay curves are measured at two beam energies because dE/dx, foil thickening, and beam divergence then differ. The decay curves are also obtained with the foil translated in both the downstream and upstream directions because foil thickening changes the time calibration differently. We now describe the results of our measurements on P II and Cu II.

2. Results

2.1. P II lifetimes
We [9] studied the P II multiplet at 1154 Å ($3s^23p^2\ ^3$P − $3s3p4s\ ^3$P^o) because the line at 1153 Å is typically used to derive phosphorus abundances. Lifetimes were measured for each of the upper levels (J = 0, 1 and 2). The lifetimes (about 0.80 ns) agreed with each other and with previous experimental results [10-11] and theoretical ones [12-15]. A second, weaker and longer decay (around 10 ns) was ascribed to a cascading transition. Theory [12, 14, 15] suggests the cascades originate from $3p4p\ ^3$D; however, we were not able to measure the lifetimes for the predicted transitions.

2.2. P II branching fractions
The intensities of the decay channels were also determined. The lines from J_u = 1 occur at 1152.8, 1155.0 and 1159.1 Å, while those for J_u = 2 are at 1150.0 and 1154.0 Å. Contamination from cascades had to be considered when deriving the intensities. The resulting branching fractions are 0.359±0.027, 0.254±0.014 and 0.387±0.026 for J_u = 1 and J_l = 0, 1 and 2, respectively, and 0.267±0.016 and 0.733±0.033 for J_u = 2 and, respectively, J_l = 1 and 2. The branching fractions differ slightly from those expected from *LS* coupling rules. However, as discussed in [9], excellent correspondence exists between our *f*-values and the theoretical ones [12, 14, 15] because the branching ratios are very similar. The measured branching fractions also agree very well with semi-empirical results [16]. An interesting consequence of the latter correspondence is described below.

2.3. Cu II lifetimes
Uncertainty surrounded the correct lifetime to use in derivations of the oscillator strength for the Cu II line at 1358 Å involving the ground state and the $3d^94p\ ^1$P^o upper state. The most recent experimental lifetime [17] is shorter than earlier measurements [18, 19]. Theoretical lifetimes [17, 20-24] tend to be shorter as well. In light of these differences, we initiated a project to determine the lifetime via beam-foil techniques. As shown in Table 1, our measured lifetime of 1.37±0.04 ns is in excellent agreement with the most recent experimental results and in general agreement with the suite of theoretical calculations. Since the theoretical branching fractions for the two main channels agree very well, a more secure *f*-value is now available for this important Cu II line.

Table 1. Lifetimes (ns) for the $3d^94p\ ^1$P^o state in Cu II.

Experiment	Present	Ref. [18]	Ref. [19]	Ref. [17]	…	…
	1.37±0.04	1.8±0.2	1.7±0.3	1.34±0.22	…	…
Theory	Ref. [20]	Ref. [21]	Ref. [17]	Ref. [22]	Ref. [23]	Ref. [24]
	1.056	0.94	0.87	1.39/1.61[a]	0.84	1.15/1.13[a]

[a] The first entry is the length formalism, the second is velocity.

3. Discussion
We presented our most recent beam-foil measurements on P II and Cu II. Ours represent the first complete set of experimental results for the P II multiplet at 1154 Å. The experimental branching fractions are in excellent agreement with large-scale calculations and semi-empirical analyses for the dipole allowed transitions. This represents the first experimental confirmation of the semi-empirical branching fractions for an ion. The semi-empirical method is based on singlet-triplet mixing in intermediate coupling when configuration interaction is negligible [16]. Our lifetime for the upper state involved in the Cu II line at 1158 Å is consistent with the most recent experimental results and theoretical determinations. Both sets of measurements are consistent with the recommendations of Ref. [25], making previously determined interstellar abundances now more secure.

The success of the semi-empirical method for branching fractions in P II suggests a technique to calibrate instrumentation involving fast beams below 2000 Å [26]. In the tin isoelectronic sequence, Sb II has the $ns^2\,np^2 - ns^2\,np\,(n{+}1)s$ transitions around 1400 Å, while the same Te III transitions are near 1000 Å, and those of Cs VI are around 400 Å. We plan to make measurements on branching fractions for this set of transitions to check the validity of the semi-empirical method at short wavelengths. As discussed in [26], the semi-empirical method may be more accurate than large-scale theoretical calculations for these ions. The ultimate goal is to determine if the semi-empirical branching fractions can be used to calibrate fast beam apparatus at far ultraviolet wavelengths.

Acknowledgments

This work was supported by NASA grants NAG 05-11440 and NNG 06-GC70G. S T acknowledges support by the US National Science Foundation under grant 0353899 as part of the Research Experience for Undergraduates.

References

[1] Dufton P L, Keenan, F P and Hibbert, A 1986 *Astron Ap* **164** 179
[2] Jenkins E B, Savage, B D and Spitzer, L 1986 *Astrophys J* **301** 355
[3] Mallouris et al 2001 *Astrophys J* **558** 133
[4] Cartledge S I B, Lauroesch, J T, Meyer, D M and Sofia U J 2006 *Astrophys J* **641** 327
[5] Molaro P, Levshakov S A, D'Odorico S, Bonifacio P and Centurión M 2001 *Astrophys J* **549** 90
[6] Levshakov S A, Dessauges-Zavadsky M, D'Odorico S and Molaro P 2002 *Astrophys J* **565** 696
[7] Pettini M, Rix S A, Steidel C C, Adelberger K L, Hunt M P and Shapley A E 2002 *Astrophys J* **569** 742
[8] Curtis L J, Berry H G and Bromander J 1971 *Phys Lett A* **34** 169
[9] Federman S R, Brown M, Torok S, Cheng S, Irving R E, Schectman R M and Curtis L J 2007 *Astrophys J* **660** 919
[10] Livingston A E, Kernahan, J A, Irwin D J G and Pinnington E H 1975 *Phys Scr* **12** 223
[11] Smith W H 1978 *Phys Scr* **17** 513
[12] Hibbert A 1988 *Phys Scr* **38** 37
[13] Brage T, Merkelis G and Froese Fischer C 1993 *Phys Lett A* **174** 111
[14] Tayal S S 2003 *Astrophys J Suppl* **146** 459
[15] Froese Fischer C, Tachiev G and Irimia A 2006 *At Data Nucl Data Tables* **92** 607
[16] Curtis L J 2000 *J Phys B* **33** L259
[17] Pinnington E H, Rieger G, Kernahan J A and Biémont E 1997 *Can J Phys* **75** 1
[18] Curtis L J, Engman B and Martinson I 1976 *Phys Scr* **13** 109
[19] Kono A and Hattori S 1982 *J Opt Soc Am* **72** 601
[20] Theodosiou C E 1986 *J Opt Soc Am B* **3** 1107
[21] Loginov A V 1993 *Phys Scr* **47** 38
[22] Donnelly D, Hibbert A and Bell K L 1999 *Phys Scr* **59** 32
[23] Biémont E, Pinnington E H, Quinet P and Zeippen C J 2000 *Phys Scr* **61** 567
[24] Dong C Z and Fritzsche S 2005 *Phys Rev A* **72** 012507
[25] Morton D C 2003 *Astrophys J Suppl* **149** 205
[26] Curtis L J, Federman S R, Torok S, Brown M, Cheng S, Irving R E and Schectman R M 2007 *Phys Scr* **75** C1