The Astrophysical Journal, 621:1159–1162, 2005 March 10

OSCILLATOR STRENGTHS FOR ULTRAVIOLET TRANSITIONS IN Cl II AND Cl III

R. M. Schectman,[1] S. R. Federman,[1] M. Brown,[1] S. Cheng,[1] M. C. Fritts,[1,2] R. E. Irving,[1] and N. D. Gibson[3]

Received 2004 November 18; accepted 2004 December 8

ABSTRACT

Oscillator strengths for transitions in Cl II and III are derived from lifetimes and branching fractions measured with beam-foil techniques. The focus is on the multiplets at 1071 Å in Cl II and 1011 Å in Cl III whose lines are seen in spectra 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 Cl II λ1071 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 these multiplets.

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

1. INTRODUCTION

The determination of abundances from the high-quality optical spectra now achievable requires oscillator strengths (*f*-values) known to 5%–10%. We present experimental lifetimes and branching fractions, from which oscillator strengths are derived, for ultraviolet transitions in Cl II and Cl III seen in spectra acquired with the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*). In particular, our beam-foil measurements involve the multiplets $3s^2 3p^4\ ^3P$–$3s3p^5\ ^3P^o$ at 1071 Å in Cl II and $3s^2 3p^3\ ^4S^o$–$3s3p^4\ ^4P$ at 1011 Å in Cl III. They are the most comprehensive single set of measurements to date, allowing us to test the applicability of *LS* coupling rules for line strengths, and they reach the level of precision needed for analysis of *FUSE* spectra.

Singly and doubly ionized chlorine represent the dominant forms of the element in many astronomical environments. In diffuse interstellar clouds that are mainly atomic, Cl occurs mostly as Cl^+ ions (Harris & Bromage 1984). *FUSE* observations of the Io torus (Feldman et al. 2001, 2004) revealed emission from Cl II and Cl III from which the total Cl abundance can be inferred; it is about 1% of the sulfur abundance.

Such studies are limited by the quantity and quality of the available atomic data used in the analysis. In Cl II, Lawrence (1969) and Bashkin & Martinson (1971) measured lifetimes for lines in the 1071 Å multiplet, and Fawcett (1986a) computed an *f*-value for the strongest line in the multiplet, while Berrington & Nakazaki (2002) calculated a multiplet *f*-value. One recent calculation (Deb et al. 2003) yielded transition probabilities for all lines in the multiplet, but the resulting lifetimes are 25% longer than the experimental ones. In another theoretical effort, Tayal (2003) studied the strong interactions between $3s^2 3p^3\ nl$ and $3s3p^5$ states. Further calculations by Tayal (2004) that included relativistic terms provided transition probabilities and *f*-values more consistent with available experimental data. The situation is similar for the data on Cl III. Of the computations, only those of Aymar (1973) are consistent with the experimental *f*-value extracted from the lifetime measured by Bashkin & Martinson (1971) for λ1015. Most of the other theoretical results (Huang 1984; Ho & Henry 1987; Ramsbottom et al. 2001; Berrington & Nakazaki 2002) yield a multiplet *f*-value that is 50% larger than the previous experimental value; Fawcett's (1986b) theoretical value is about 30% smaller.

In this paper we present new beam-foil measurements that attempt to clarify the situation. In the next section, we describe the experiment where we measured lifetimes for each of the upper levels in the two multiplets of interest, as well as branching fractions for transitions originating from the $j = 1$ and 2 levels of the $^3P^o$ term in Cl II. This is followed by a section on our results and a discussion of them. Section 4 gives a summary of our measurements on Cl II and Cl III.

2. EXPERIMENTAL DETAILS

We carried out our experiments with the beam-foil facility at the Toledo Heavy Ion Accelerator (Haar et al. 1993). Cl^+ ions were selected by passing them through a bending magnet and then were accelerated to final energies of 170 or 220 keV. Typical beam currents were 70 nA. Upon passage through carbon foils with thicknesses of 2.2–2.5 μg cm^{-2}, the ions 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 dispersed the radiation from the decaying ions onto a channeltron detector. A search for decays from levels that could repopulate the upper states of interest ($3s3p^5\ ^3P^o$ in Cl II and $3s3p^4\ ^4P$ in Cl III) with wavelengths between 1500 and 2000 Å utilized a 1200 line mm^{-1} grating blazed at 1500 Å.

Various measurements were performed to account for systematic effects. The stability of the ion beam was monitored downstream of the entrance slit to the monochromator by recording the number of ions entering a Faraday cup and by detecting visible light from decays of excited ions in the beam with a phototube (the optical monitor). Only decay curves and spectra where both monitors fluctuated in unison and by less than 20% were analyzed further. All analyses were based on decay curves and spectra that were normalized using the optical monitor. The effects of beam divergence, foil thickening, and nuclear scattering were examined through measurements of decay curves at two energies and in both the forward and reverse directions (e.g., Federman et al. 1992). Finally, a search for decays leading to repopulation revealed that the strongest of these cascades are much weaker than the transitions of interest, so weak in fact that we could not apply the method of arbitrarily normalized decay

[1] Department of Physics and Astronomy, University of Toledo, Toledo, OH 43606; rms@physics.utoledo.edu, steven.federman@utoledo.edu, mbrown@physics.utoledo.edu, scheng@physics.utoledo.edu, rirving@physics.utoledo.edu.

[2] School of Physics and Astronomy, University of Minnesota, 116 Church Street SE, Minneapolis, MN 55455; fritts@physics.umn.edu.

[3] Department of Physics and Astronomy, Denison University, Granville, OH 43023; gibson@denison.edu.

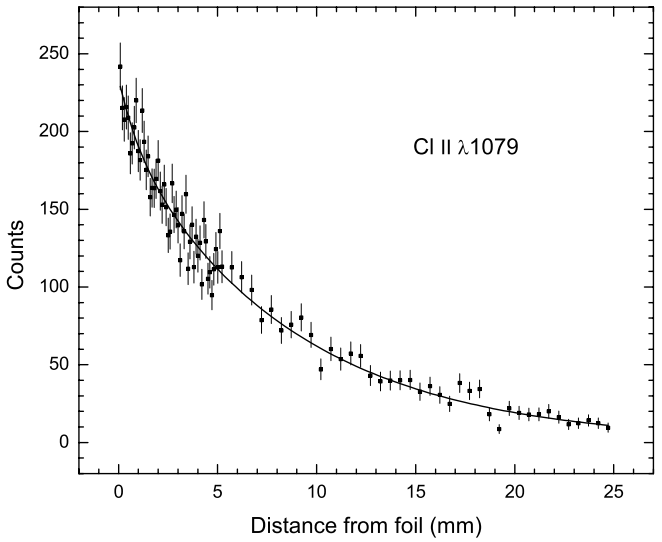

FIG. 1.—Measured Cl II decay curve for the line at 1079 Å for a beam energy of 170 keV. The postfoil beam velocity at this energy was 0.9451 mm ns^{-1}, thus establishing the time since excitation for a given foil position. The foil was moved relative to the monochromator entrance slit in increments of 0.1 mm until it was displaced 5 mm; then it was moved in increments of 0.5 mm. The two-exponential fit to the data without background correction is shown by the solid curve.

curves (ANDC) as a correction (see Curtis et al. 1971). Such a result is consistent with the findings of Bashkin & Martinson (1971), who quoted a replenishment ratio of 0.

Decay curves were obtained for each value of j in the upper fine-structure levels associated with the multiplet at 1071 Å in Cl II and 1011 Å in Cl III. This provided one way of determining the applicability of *LS* coupling rules to these transitions from the resulting lifetimes. The lifetimes were extracted from the curves via multiexponential fits with and without background correction. The lines of Cl II showed the presence of a second very rapid decay (about 1 ns). We attribute the rapid decay to transitions in Cl IV and V detected in second order; these blends are discussed in more detail below. Single-exponential fits, at greater and greater distances from the foil, gave a lifetime that converged to the value obtained from the two-exponential fit.

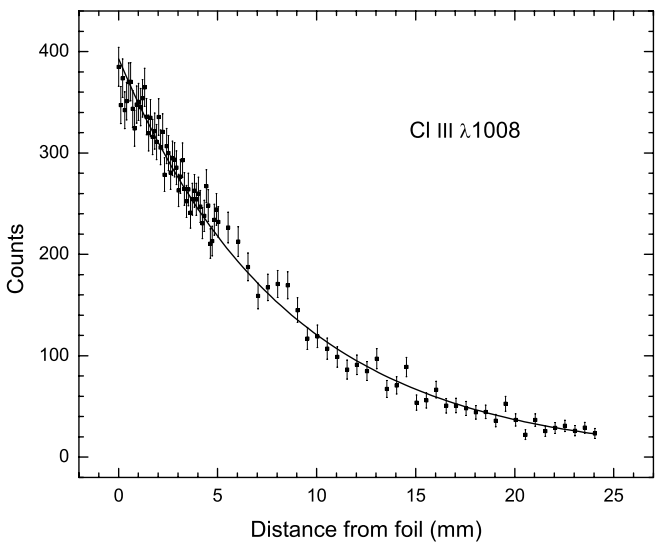

FIG. 2.—Same as Fig. 1, but for the 1008 Å line in Cl III acquired at 220 keV, with a single-exponential fit shown.

TABLE 1
Cl II LIFETIMES

j_u	λ_{ul} (Å)	τ (ns) Present	L[a]	BM[b]	DCFM[c]	T[d]
2.....	1079.08	9.14 ± 0.43	8.37 ± 0.5	7.5 ± 0.8[e]	11.6	9.82
1.....	1063.83	8.30 ± 0.42	9.42 ± 0.2	...	11.1	9.84
0.....	1067.95	8.49 ± 0.48	...	...	12.1	9.80

[a] Lawrence (1969); pulsed electron.
[b] Bashkin & Martinson (1971); beam foil.
[c] Deb et al. (2003); configuration interaction calculation.
[d] Tayal (2004); Hartree-Fock calculation with relativistic corrections.
[e] Used line at 1071.04 Å.

Examples of decay curves appear in Figures 1 and 2 for Cl II and Cl III, respectively.

When an upper level has more than one channel for decay, branching fractions are needed to convert lifetimes into oscillator strengths. Since decays to excited terms in the lowest energy state via intercombination lines are quite weak, branching fractions only for transitions within the Cl II multiplet at 1071 Å had to be measured. This was accomplished by determining the relative integrated intensities from lines with a common upper level through fits based on Gaussian and Voigt line profiles. In particular, for $j = 1$ the lines are $\lambda\lambda$1064, 1072, 1075, and for $j = 2$ they are $\lambda\lambda$1071, 1079.

Initially, a complication arose during these measurements: most of the Cl II lines were broader than expected. The broadening was the result of contamination from blends of strong lines from Cl IV and V near 535 Å appearing in second order. By placing the foils 3.8 mm (∼4 ns) upstream of the monochromator entrance slit, the width of the Cl II lines became more consistent with our experimental line widths (Gaussian widths of about 0.22 Å) because the intensity of the contaminating lines had then decayed to nearly imperceptible levels. We attribute the shorter lifetimes found in the decay curves to these transitions in Cl IV and V, since such short lifetimes are commonly found in dipole-allowed transitions from highly charged ions. While somewhat surprising for the relatively low beam energies in our experiments, further confirmation of the presence of Cl IV and V comes from detection of other transitions in these ions (e.g., Cl IV $\lambda\lambda$466, 467 and Cl V $\lambda\lambda$883, 894), also in second order, during the search for possible cascades.

3. RESULTS AND DISCUSSION

3.1. *Lifetimes and Oscillator Strengths*

The results of our lifetime measurements for $3s3p^5\ ^3P^o$ in Cl II and $3s3p^4\ ^4P$ in Cl III appear in Tables 1 and 2, along with other

TABLE 2
Cl III LIFETIMES

j_u	λ_{ul} (Å)	τ (ns) Present	BM[a]	H[b]
5/2	1015.02	8.13 ± 0.31	10.7 ± 0.8	7.14[c]
3/2	1008.78	7.89 ± 0.32	...	6.90[c]
1/2	1005.28	7.87 ± 0.43	...	7.23[c]

[a] Bashkin & Martinson (1971); beam foil.
[b] Huang (1984); Dirac-Fock calculation with relativistic corrections.
[c] Based on A-values derived from quoted f-values and experimental wavelengths.

TABLE 3
Cl II Oscillator Strengths

λ_{ul} (Å)	j_l	j_u	f-Value ($\times 10^{-3}$)								
			Present[a]	Present (LS)[b]	L[c]	BM[d]	F[e]	BN[f]	DCFM[g]	T[h]	M[i]
1079.08	1	2	7.8 ± 0.4	8.27 ± 0.41	...	...	...	...	6.2	7.72/9.07[j]	8.3 ± 0.3
1075.23	0	1	...	19.84 ± 0.99	...	...	...	...	15.5	18.3/20.9	19.9 ± 0.7
1071.77	1	1	...	4.96 ± 0.25	...	...	...	...	3.9	4.53/5.12	5.0 ± 0.2
1071.04	2	2	14.2 ± 0.7	14.88 ± 0.74	...	...	2.2	...	11.2	13.8/16.0	15.0 ± 0.5
1067.95	1	0	6.7 ± 0.4	6.61 ± 0.33	...	...	...	...	4.7	6.10/7.14	6.7 ± 0.2
1063.83	2	1	...	4.96 ± 0.25	...	...	...	...	4.0	4.61/5.11	5.0 ± 0.2
Multiplet	...	...	...	19.84 ± 0.99	18.5 ± 0.4	22.9 ± 2.4	...	19.2	...	18.4/21.2	20.0

[a] From present measurements.
[b] From present measurements assuming LS coupling applies.
[c] Lawrence (1969).
[d] Bashkin & Martinson (1971).
[e] Fawcett (1986a); Hartee-Fock calculation with relativistic corrections.
[f] Berrington & Nakazaki (2002); ***R***-matrix calculation.
[g] Deb et al. (2003).
[h] Tayal (2004).
[i] Morton (2003) compilation.
[j] First entry based on length formalism, the second on velocity formalism.

determinations. The lifetimes from Deb et al. (2003) and Tayal (2004) in Table 1 are based on their calculated A-values, while those from Huang (1984) in Table 2 come from the computed f-values and experimental wavelengths. (The transition rates, called R, in Huang are inferred from wavelengths determined theoretically.) Our lifetimes for Cl II agree with the earlier experimental values of Lawrence (1969) and Bashkin & Martinson (1971). However, the theoretical results of Deb et al. (2003) based on calculations that included configuration interaction are about 25% larger. The more extensive calculations of Tayal (2004) agree much better with the experimental results. Our lifetimes for the three upper levels, $j = 2$, 1, and 0, are consistent with their weighted mean of 8.65 ns within the uncertainty of ~5% for each measurement, suggesting that to this accuracy LS coupling rules apply. For Cl III, the correspondence with the experimental lifetime for $j = 5/2$ (Bashkin & Martinson 1971) is less satisfactory; our value differs from theirs by more than 3 times the combined uncertainties of measurement. For these transitions, there is better agreement between our measurements and the Dirac-Fock results of Huang (1984). As was the case for Cl II, our lifetimes and those assuming LS coupling agree very nicely.

Table 3 compares the f-values inferred from our lifetimes and branching fractions for Cl II with earlier experimental measurements. Blending prohibited us from obtaining a sufficiently accurate complete set of branching fractions for transitions from the $j = 1$ level to enable us to determine accurate f-values involving this level. On the other hand, we see in the next section that the predictions of LS coupling are verified to within the accuracy of our measurements; consequently, we also present in Table 3 oscillator strengths derived from our lifetimes under the assumption that LS coupling holds. Theoretical results for all lines of the multiplet are also presented for comparison, as are the most recent recommendations of Morton (2003), which here are based on experimental data. For the Cl II multiplet, our f-value of $(19.84 \pm 0.99) \times 10^{-3}$ is in reasonable agreement with the values derived from the experimental lifetimes of Lawrence (1969) and Bashkin & Martinson (1971), and it agrees very well with the determination from ***R***-matrix calculations (Berrington & Nakazaki 2002). The poor agreement with the theoretical f-value

TABLE 4
Cl III Oscillator Strengths

λ_{ul} (Å)	j_l	j_u	f-Value ($\times 10^{-2}$)								
			Present	BM[a]	A[b]	H[c]	F[d]	HH[e]	RBK[f]	BN[g]	M[h]
1015.02	3/2	5/2	2.85 ± 0.11	...	...	3.24	0.97	...	...	...	2.14 ± 0.15
1008.78	3/2	3/2	1.93 ± 0.08	...	...	2.21	0.92	...	...	...	1.44 ± 0.10
1005.28	3/2	1/2	0.96 ± 0.05	...	...	1.05	0.90	...	...	...	0.72 ± 0.05
Multiplet	...	...	5.74 ± 0.15	4.3 ± 0.3	4.0	6.50	2.78	6.5[i]	6.1	6.58[i]	4.3
	...	...	...	...	...	...	...	6.8[j]	...	5.91[j]	...

[a] Bashkin & Martinson (1971).
[b] Aymar (1973); effective potential calculation with configuration interaction.
[c] Huang (1984).
[d] Fawcett (1986b); Hartree-Fock calculation with relativistic corrections.
[e] Ho & Henry (1987); Hartree-Fock calculation with configuration interaction.
[f] Ramsbottom et al. (2001); ***R***-matrix calculation.
[g] Berrington & Nakazaki (2002).
[h] Morton (2003) compilation.
[i] Based on length formalism.
[j] Based on velocity formalism.

of Fawcett (1986a) arises from configuration interaction. Our results for Cl II are in excellent agreement with the extensive Hartee-Fock calculation of Tayal (2004) and with the recommendations of Morton (2003). Thus, there is no need to revise interstellar Cl^+ abundances obtained previously that are based on these recommendations.

For Cl III, our *f*-values are presented in Table 4, where they are compared with previous experiment and theory. Our results are consistent with most recent theoretical efforts (Huang 1984; Ho & Henry 1987; Ramsbottom et al. 2001; Berrington & Nakazaki 2002). These large-scale computations are based on a variety of methods: Dirac-Fock with relativistic corrections (Huang 1984), Hartree-Fock with configuration interaction (Ho & Henry 1987), and ***R***-matrix (Ramsbottom et al. 2001; Berrington & Nakazake 2002). On the other hand, the correspondence with the measurement of Bashkin & Martinson (1971) and the calculations of Aymar (1973) and Fawcett (1986b) is poor. Fawcett noted that his results for Cl III were also prone to large errors because substantial amounts of configuration interaction were likely. 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.

3.2. *LS Coupling*

Our measurements of lifetimes from each upper level of interest in Cl II and III and of branching fractions for transitions within the 1071 Å multiplet in Cl II provide a test of *LS* coupling rules. The very good correspondence between the measured lifetimes for each of the upper fine-structure levels and those expected when *LS* coupling applies was noted above. Here we focus on branching ratios. For reference, Figure 3 displays a spectrum of the multiplet at 1071 Å taken with foils 3.8 mm upstream of the slit. The results for transitions from the $j = 2$ fine-structure level are discussed first because they were least affected by contamination from Cl IV and V lines. A weighted sum of results from 10 spectral scans yielded a branching fraction, $I(1079)/I(1071)$, of 0.325 ± 0.008 from Gaussian fits that is indistinguishable from the branching fraction of 0.326 computed from *LS* coupling rules. Fits with a Voigt function produced similar although less precisely determined fractions. Three lines result from transitions originating from the $j = 1$ level. However, in addition to contamination from Cl IV and V, the Cl II line at 1072 Å is the weakest line in our spectrum and is blended with the strongest line (λ1071). Therefore, only the lines at 1075 and 1064 Å provided useful tests of *LS* coupling. The resulting branching ratio from a weighted sum of eight spectra was $I(1075)/I(1064) = 0.824 \pm 0.037$. This also compares favorably with the value inferred from *LS* coupling, 0.773. In summary, our lifetimes and branching fractions indicate that *LS* coupling applies to the two multiplets under study to within the ($\leq$5%) accuracy of our measurements.

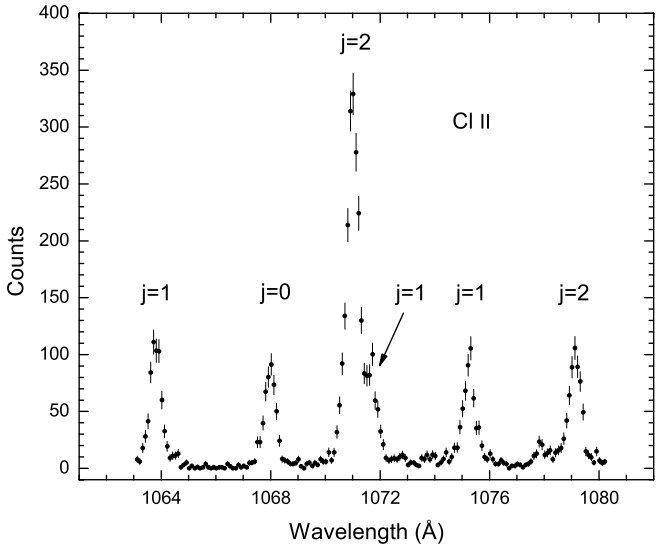

FIG. 3.—Spectrum of the Cl II multiplet at 1071 Å taken with the foil 3.8 mm upstream of the entrance slit to the monochromator. The total angular momentum quantum number for each upper fine-structure level is indicated.

4. CONCLUSIONS

We have presented the most comprehensive set of measured lifetimes and branching fractions for the multiplets $3s^2 3p^4\ ^3P$–$3s3p^5\ ^3P^o$ at 1071 Å in Cl II and $3s^2 3p^3\ ^4S^o$–$3s3p^4\ ^4P$ at 1011 Å in Cl III to date. These data were used to derive oscillator strengths for all the lines in the two multiplets to a typical accuracy of 4%–5%. A comparison with the *f*-values recommended by Morton (2003), which are mainly based on previous experimental results, revealed excellent agreement for the lines in the Cl II multiplet. Similar levels of agreement are found when comparison is made with the theoretical results of Tayal (2004). For the Cl III multiplet, however, the correspondence is not as good. While our measurements yield *f*-values consistent with the results from recent large-scale theoretical calculations, Morton's (2003) suggested values are 30% smaller. Our extensive set of measurements also verified the use of *LS* coupling rules for individual line strengths within the two multiplets.

We thank Paul Feldman for providing us with his results before publication. This work was supported by NASA grant NAG5-11440 to the University of Toledo.

REFERENCES

Aymar, M. 1973, Nucl. Instrum. Methods, 110, 211
Bashkin, S., & Martinson, I. 1971, J. Opt. Soc. Am., 61, 1686
Berrington, K. A., & Nakazaki, S. 2002, At. Data Nucl. Data Tables, 82, 1
Curtis, L. J., Berry, H. G., & Bromander, J. 1971, Phys. Lett. A, 34, 169
Deb, N. C., Crothers, D. S. F., Felfli, Z., & Msezane, A. Z. 2003, J. Phys. B, 36, L47
Fawcett, B. C. 1986a, At. Data Nucl. Data Tables, 35, 185
———. 1986b, At. Data Nucl. Data Tables, 35, 203
Federman, S. R., Beideck, D. J., Schectman, R. M., & York, D. G. 1992, ApJ, 401, 367
Feldman, P. D., Ake, T. B., Berman, A. F., Moos, H. W., Sahnow, D. J., Strobel, D. F., Weaver, H. A., & Young, P. R. 2001, ApJ, 554, L123
Feldman, P. D., Strobel, D. F., Moos, H. W., & Weaver, H. A. 2004, ApJ, 601, 583
Haar, R. R., Beideck, D. J., Curtis, L. J., Kvale, T. J., Sen, A., Schectman, R. M., & Stevens, H. W. 1993, Nucl. Instrum. Methods Phys. Res. B, 79, 746
Harris, A. W., & Bromage, G. E. 1984, MNRAS, 208, 941
Ho, Y. K., & Henry, R. J. W. 1987, Phys. Scr., 35, 831
Huang, K.-N. 1984, At. Data Nucl. Data Tables, 30, 313
Lawrence, G. M. 1969, Phys. Rev., 179, 134
Morton, D. C. 2003, ApJS, 149, 205
Ramsbottom, C. A., Bell, K. L., & Keenan, F. P. 2001, At. Data Nucl. Data Tables, 77, 57
Tayal, S. S. 2003, J. Phys. B, 36, 3239
———. 2004, A&A, 426, 717