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ATOMIC TRANSITION PROBABILITIES: NEW MEASUREMENTS FOR LIGHT ELEMENTS*

by

Myron H. Miller

University of Maryland
College Park, Maryland

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Abstract

A list of newly measured atomic transition probabilities is given for visible lines of carbon, sulphur, phosphorous and silicon, i.e., CI, SI, SII, PI, PII, SiI and SiII. These results are communicated while final publications are being prepared, so that the numbers can be of use in astrophysical abundance determinations, etc. The spectroscopic source is a gas-driven shock tube operating between 9000 and 13000° K. Plasma conditions are directly determined by a variety of methods, including some new ones which automatically circumvent temperature errors. The list of line strengths covers 136 lines, 84 of which are unblended in the shock tube spectra. The 46 multiplets involved include 39 which are observed in their entirety, 28 of these being fully resolved. Upper limit estimates are attached to 31 additional lines, 17 of which are unblended. Accuracies as well as precisions are typically 20%; the range of accuracies is 10% to 40%. A few numbers may be changed by small amounts in a final review of the data; any such modification will be reported in published papers which will also give full details of procedures, results, and comparisons with theory.

Introduction

The line strengths listed in this report were measured photoelectrically and photographically, primarily in emission, using the hot gas behind a reflected shockwave in a shock tube as the spectroscopic source. This technique (and the closely related one of using the lower temperature, moving gas behind the primary shockwave) is becoming well-known because of its many advantages over other thermal light sources. The main problem of having to time-resolve every experiment in order to separate out the interval of interest (~100 microseconds) is overcome fairly readily, so that many direct measurements of the state of the gas are made with time resolutions of order 0.5-5 microseconds.

Also, the classical difficulty with all thermal sources of atomic lines--*i.e.*, Sensitivity of level populations to temperature errors--can now be overcome by methods of "thermal balancing" which we have developed and used to automatically compensate for systematic errors. Questions of gas composition and local thermal equilibrium are also readily settled when one uses certain groups of simultaneous measurements of state variables as opposed to the "bare minimum" of two familiar from classical thermodynamics.

For these and other reasons, then, we have been pursuing a program of line strength measurements with the shock tube, for the light elements which are also the most abundant astrophysically. We will later return to studies of the moderately and very heavy elements. This report covers a portion of the light element studies, namely most of the visible lines for atoms and ions of carbon, silicon, phosphorus and sulphur.

The wavelength regions for the various species are:

	CI	SiI & SiII	PI & PII	SI & SII
λ-range (Ångstroms)	4000-6000	4600-6300	4600-6100	4000-6800

In these regions we have left out, for each species, about 10-15% of the lines strong enough to measure well. This is due partly to interference from hydrogen and neon lines; neon is our carrier gas for spectroscopic additives, and hydrogen is a common additive for diagnostic purposes. Another factor is blending of comparably strong lines from different multiplets. Also a few cases in SiI and PII have not yet been treated because of uncertain classifications.

2. Results

Measured transition probabilities are listed for the above species in Table 1-6, as the Einstein coefficient for spontaneous emission, A_{mn}, in inverse seconds X specified powers of 10. We also list [$\log_{10} gf$] where g is the degeneracy $2J + 1$ of the lower level (n) and f the absorption oscillator strength. We use the "multiplet numbers" of Mrs. (Moore) Sitterley's well-known astrophysical compilation, giving also the terms and J-values for the levels involved. Wavelengths are in Ångstroms; the "remarks" in the tables are self-explanatory and may be helpful in applying the data to abundance determinations.

Tolerances stated in the tables are best estimates of <u>total</u> error. They represent the RMS combination of uncertainty due to scatter (random error) with the uncertainty compounded by estimated possible systematic errors in measured variables. For each atom (ion) studied, the one line designated as being "measured absolutely" has the smallest tolerance. This is because such lines are the strongest isolated ones studied, are the lines most carefully checked for self-consistency, and are usually measured the maximum number of times for that atom. The range of tolerance for these lines runs from ±10% for C_I $\lambda 5052$ to ±25% for Si_I $\lambda 5948$. For these lines the scatter is responsible for only a small fraction of the total tolerance whether 44 independent determinations as for C_I or only 5 determinations as for P_I have been made. Since all other lines of an element were measured relative to one of these lines, their assigned tolerances are no better than for the relevant "absolutely measured" line. In general, they warrant larger tolerances (15% - 45%) because of such factors as low signal-to-noise ratio, difficulties in the interpretation of diffuse or partially merged lines, uncertainty in relative film sensitivity between widely spaced wavelengths and, in a few cases lack of a sufficient number of determinations to permit a statistical statement.

Table 1. TRANSITION PROBABILITIES FOR C_I †

Multiplet	Transition (n, lower) (m, upper)	J_n-J_m	λ(Å)	Amn $10^6 sec^{-1}$	$\log_{10}$ gf	Tolerance	Remarks
4	3s $^3P^o$ - 4p ^3D	2-3	5041.6				
		1-2	5039.0				
		0-1	5039.0	.42	-1.595	±35%	(1)
		2-2	5049.6				
		1-1	5044.0				
5	3s $^3P^o$ - 4p ^3S	2-1	4826.7	< .31	<-2.488	----	(2)
		1-1	4817.3	< .19	<-2.702	----	
		0-1	4812.8	< .10	<-2.982	----	
6	3s $^3P^o$ - 4p ^3P	2-2	4771.7				
		1-1	4766.6				
		2-1	4775.8	1.39	-1.370	20%	(3)
		1-0	4770.0				
		1-2	4762.4				
		0-1	4762.4				
7	3s $^3P^o$ - 5p ^3D	2-3?	4065.1				
		1-2?	4064.2	< .04	<-2.828	----	(2)
		0-1?	4064.2				
11	3s $^1P^o$ - 4p ^1P	1-1	5380.2	1.72	-1.650	15%	
12	3s $^1P^o$ - 4p ^1D	1-2	5052.1	1.74	-1.478	10%	(4)
13	3s $^1P^o$ - 4p ^1S	1-0	4932.0	3.51	-1.893	15%	
14	3s $^1P^o$ - 5p ^1P	1-1	4371.3	.59	-2.295	30%	(5)
15	3s $^1P^o$ - 5p ^3D	1-2?	4352.1	< .17	<-2.617	----	(2)
16	3s $^1P^o$ - 5p ^1D	1-2	4268.9	.26	-2.450	30%	
17	3s $^1P^o$ - 5p ^1S	1-0	4231.3	.70	-2.726	35%	(5)
18	$2p^3$ $^3D^o$ - 4p ^3P	3-2	5793.5				
		2-1	5801.1	.35	-1.799	35%	(5)
		1-0	5805.7				

†Listed multiplets are effectively complete.

Remarks: (1) The large tolerance assigned these merged lines stems both from their weakness and from their diffuse appearance, which might mask blending with a predicted C_I recombination feature. (2) When lines are detectable, but have marginal signal-to-noise ratios, the grainy profiles are interpreted to contain the maximum conceivable energy. (3) For a small percentage of the data, members of this multiplet could be partially resolved: to within the error limits of these observations LS coupling described the relative line strengths with the multiplet. (4) This transition was measured absolutely: all other C_I transitions were measured relative to it. (5) A large tolerance attaches to these results both because the lines are weak and because relatively few films were exposed at these wavelengths.

Table 2. TRANSITION PROBABILITIES FOR Si_{I} †

Multiplet	Transition (n, lower)(m, upper)	J_n-J_m	λ(Å)	Amn $10^7 sec^{-1}$	$\log_{10} gf$	Tolerance	Remarks
9	$4s\ ^3P^o - 5p\ ^3D$	2-3	5797.9 }	.019	-1.935	±35%	(1)
		1-2	5793.1 }				
		0-1	5780.4	.031	-2.335	35%	
		2-2	5859.2	< .002	< -3.306	----	
10	$4s\ ^3P^o - 5p\ ^3P$	2-2	5708.4 }	.140	-1.211	35%	(2)
		1-1	5690.5 }				
		2-1	5754.3 }				
		1-0	5701.1 }				
		1-2	5645.7 }				
		0-1	5665.6 }				
11	$4s\ ^3P^o - 5p\ ^3S$	2-1	5684.5	.085	-1.910	35%	
		1-1	5622.2	< .006	< -3.086	----	
11.05*	$4s\ ^3P^o - 6p\ ^3P$	2-2	4792.3 }	.011	-2.644	40%	
		1-0	4792.2 }				
16	$4s\ ^1P^o - 5p\ ^1D$	1-2	5948.5	.098	-1.585	35%	
17	$4s\ ^1P^o - 5p\ ^1S$	1-0	5772.2	.175	-2.058	35%	(3)
21.10*	$3p^3\ ^3D^o - 5f[2\frac{1}{2}]$ }	$g_m \equiv 26$ } (4)		.108	- .529	40%	(4)
21.11*	$3p^3\ ^3D^o - 5f[3\frac{1}{2}]$ }						
38.03*	$4p\ ^1P - 7d\ ^1D^o$ }	$\lambda\lambda \approx 6245$ }					
21.12*	$3p^3\ ^3D^o - 5f'\ [3\frac{1}{2}]$ }	$g_m \equiv 42$ } (4)		.054	- .892	40%	(4)
21.13*	$3p^3\ ^3D^o - 5f'\ [2\frac{1}{2}]$ }						
21.14*	$3p^3\ ^3D^o - 5f\ [1\frac{1}{2}]$ }	$\lambda\lambda \approx 6150$ }					
	TRANSITION PROBABILITIES FOR Si_{II} †						
2	$4\ ^2S - 4\ ^2P^o$	$\frac{1}{2}$-$1\frac{1}{2}$	6347.1	3.10	- .097	±40%	(5)
		$\frac{1}{2}$-$\frac{1}{2}$	6371.3	3.87	- .331	40%	(5)
4	$4\ ^2P^o - 5\ ^2S$	$1\frac{1}{2}$-$\frac{1}{2}$	5978.9	5.27	- .247	30%	
		$\frac{1}{2}$-$\frac{1}{2}$	5957.6	3.56	- .413	30%	
5	$4\ ^2P^o - 4\ ^2D$	$1\frac{1}{2}$-$2\frac{1}{2}$	5056.0 }	3.8	.167	20%	(6)
		$1\frac{1}{2}$-$1\frac{1}{2}$	5056.3 }				
		$\frac{1}{2}$-$1\frac{1}{2}$	5041.0	4.73	- .143	20%	

†All members of given multiplets are measured.

*Revised classification from C. E. Moore, NRDS-NBS 3, Section 2.

Remarks: (1) For merged members of the same multiplet take $A = \sum_i g_i A_i / \sum_i g_i$. (2) Lines of this multiplet merge into a broad, prominent feature; $A = \sum_J g_J A_J / (2L + 1)(2S + 1)$. (3) This transition measured absolutely; other Si_I lines are measured relative to it. (4) These several multiplets are merged into broad conspicuous features; since differences in these energy levels are not significant at $T \approx 1.0$ ev, the A-value given is $A_{mn} \equiv \sum (gA) / g_m$, g_m defined above. (5) These lines are strong and isolated, but accuracy of their measurement is degraded to 40% because they fall near edge of film in a region of vignetting. (6) This transition measured absolutely; other Si_{II} lines are measured relative to it.

Table 3. TRANSITION PROBABILITIES FOR P_I

Transition† (n, lower) (m, upper)	J_n-J_n	λ(Å)	Amn $10^6 sec^{-1}$	log_{10} gf	Tolerance	Remarks
$4s\ ^4P - 5p\ ^4S^\circ$	1½-1½	5015.8	.24	-2.438	±45%	
	2½-1½	5079.3	.73	-1.949	30%	
$4s\ ^4P - 5p\ ^4P^\circ$	½-1½	5061.9	.48	-2.129	35%	
	1½-½	5098.2 }	.44	-1.990	30%	
	1½-1½	5100.9 }				
	2½-2½	5109.6	.48	-1.945	35%	
$4s\ ^4P - 5p\ ^4D^\circ$	½-1½	5149.4 }	.24	-1.761	35%	(3)
	1½-2½	5154.8 }				
	2½-3½	5162.2 }				
$4s\ ^2P - 5p\ ^2P^\circ$	1½-1½	5345.8	1.61	-1.561	35%	(3)
$4s\ ^2P - 5p\ ^2D^\circ$	½-1½	5458.3	1.85	-1.482	40%	(2), (3)
	1½-2½	5477.7	2.92	-1.103	30%	(1), (2)
$3p^4\ ^4P - 4f\ ^4D^\circ$	1½-2½	5514.7 }	1.14	-1.137	30%	(3)
	2½-3½	5517.0 }				
$3p^4\ ^4P - 4f\ ^2D^\circ$	½-1½	5546.9	.51	-2.030	30%	(3)
$4s\ ^2P - 5p\ ^2S^\circ$	1½-½	5905.0	.37	-2.408	40%	(4)

†Classification from W. C. Martin, *J. Opt. Soc. Amer.* 49, 1071 (1959).

Remarks: (1) This transition measured absolutely; other P_I transitions measured relative to it. (2) Under shock tube conditions each of these lines is merged with some other P_I line belonging to a different multiplet. The results of MARTIN were employed in the analysis of these line pairs which we feel is justified when one of the merged pairs is at least four times stronger than the other according to his relative intensity estimates: only the stronger members of the pair are then reduced to A-values. (3) These P_I lines are merged with P_{II} lines, but reduction to A-values is possible for source conditions where the P_{II} line is not more than 1/4 the strength of the P_I line. (The P_{II} lines in question can be enhanced to 10 times the brigthness of any observed P_I line, so their A-values may be obtained by going to higher source temperatures. The P_I A-values are small and the P_I lines arise from low energy states while the P_{II} A-values are very large but arise from high energy states. By shifting source temperatures ±3000°K one can effectively suppress or enhance either the P_I or P_{II} spectrum.) (4) This line merged with the line Neon I λ5906.4, but approximate correction for this interference is made in an analogous fashion to that given in remark (3).

Table 4. TRANSITION PROBABILITIES FOR P_{II}

Multiplet	Transition (n, lower)(n, upper)	J_n-J_m	$\lambda(\mathring{A})$	Amn $10^8 sec^{-1}$	$\log_{10}$ gf	Tolerance	Remarks
5	$4s\ ^3P^o - 4p\ ^3D$	2-3	6043.1	.73	.447	±35%	(1)
		1-2	6024.1	.30	- .043	35%	
		1-1	6087.8	.24	- .395	35%	
6*	$4s\ ^3P^o - 4p\ ^3P$	2-2	5425.9	1.12	.393	25%	
		1-1	5386.9	.55	- .142	25%	
		2-1	5499.7	.31	- .374	20%	
		1-0	5409.7	1.43	- .202	25%	
		0-1	5344.7	.66	- .074	30%	
		1-2	5316.1	.29	- .207	25%	
7*	$4s\ ^3P^o - 4p\ ^3S$	2-1	5296.1	.86	.036	30%	
		1-1	5191.4	.19	- .638	25%	
		0-1	5152.2	< .02	< -1.686	----	
10*	$4s\ ^1P^o - 4p\ ^1D$	1-2	5253.5	1.15	.375	20%	(2)
13	$4p\ ^3D - 5s\ ^3P^o$	3-2	4943.4	1.28	.371	25%	
		2-1	4969.6	.68	- .121	30%	
		1-0	4954.3	.68	- .601	25%	
		1-1	4927.0	.36	- .403	30%	
15	$4p\ ^3D - 4d\ ^3F^o$	3-4	4602.1	1.72	.692	35%	
		3-3	4658.3	2.52	.759	35%	
23*	$4p\ ^3P - 5s\ ^3P^o$	2-2	5450.7	.85	.278	35%	(3)
		1-1	5507.1	.53	- .144	35%	
		2-1	5583.3	.51	- .146	35%	
		1-0	5541.2	.98	- .344	35%	
		1-2	5378.1	.39	- .075	30%	
		0-1	5483.6	.70	.024	35%	
27*	$4p\ ^3S - 5s\ ^3P^o$	1-2	5588.2	.38	- .051	35%	(3)
		1-1	5727.7	.28	- .377	45%	

*Measurement secured for all members of multiplet.

Remarks: (1) Accuracy for this multiplet is degraded (to ±35%) because only two observations were made at this wavelength. (2) This transition was measured absolutely; all other P_{II} transitions are measured relative to it. (3) For these multiplets the lines are relatively weak so that the measurements suffer from low signal-to-noise ratios.

Table 5. TRANSITION PROBABILITIES FOR MERGED† S_I MULTIPLETS

Multiplet	Transition (n, lower)(m, upper)	$\lambda(\mathring{A})$**	Amn * $10^6 sec^{-1}$	$\log_{10} gf$	Tolerance	Remarks
2	$4\ ^5S^o - 5\ ^5P$	4695	.58	-1.541	±15%	(1)
4	$4\ ^3S^o - 5\ ^3P$	5278	.33	-1.906	20%	
5	$4\ ^3S^o - 6\ ^3P$	4411	<.04	< -2.98	----	
..	$4s\ ^3S^o - 4p\ ^3P$	4154	.18	-2.378	45%	(2)
8	$4\ ^5P - 5\ ^5D^o$	6752	6.0	.0108	35%	(3)
10	$4\ ^5P - 6\ ^5D^o$	6409	<.18	< -1.56	----	
11	$4\ ^5P - 7\ ^5D^o$	5701	<.07	< -2.07	----	
12	$4\ ^5P - 8\ ^5D^o$	5503	<.04	< -2.34	----	

† Range of electron densities; $5 < Ne < 12 \times 10^{16}/cc$.

** Approximate wavelength of peak intensity.

* For merged multiplets: $A_{mn} = \sum_J g_J A_J / (2L + 1)(2S + 1)$.

.. Multiplet given by Frerichs (1933).

Remarks: (1) This multiplet measured absolutely; other S_I multiplets measured relative to it. (2) Several lines of S_{II} are superimposed on this multiplet, their interference being approximately compensated for. (3) This is a strong, well-defined feature, the accuracy of the A-value being degraded (to ±35%) because only two observations were made.

Table 6. TRANSITION PROBABILITIES FOR S_{II}

Multiplet	Transition (n, lower)(m, upper)	J_n-J_m	$\lambda(\mathring{A})$	Amn $10^8 sec^{-1}$	$\log_{10}$ gf	Tolerance	Remarks
1*	3s $3p^4$ ^2P - 4p $^2S^o$	1½-½	5027.1	.30	- .643	±20%	
		½-½	5142.3	.25	- .703	25%	
6*	4s ^4P - 4p $^4D^o$	2½-3½	5453.6	1.06	+ .578	15%	(1)
		1½-2½	5432.7	.84	+ .348	15%	
		½-1½	5428.6	.50	- .054	15%	
		2½-2½	5564.9	.23	- .193	20%	
		1½-1½	5509.6	.57	+ .016	15%	
		½-½	5473.6	1.11	- .001	15%	
		2½-1½	5645.6	< .20	< - .418	----	
		1½-½	5556.0	.28	- .587	35%	
7*	4s ^4P - 4p $^4P^o$	2½-2½	5032.4	.69	+ .196	20%	
		1½-1½	4991.9	.29	- .363	20%	
		½-½	4942.4	.22	- .793	25%	
		2½-1½	5103.3	.44	- .163	20%	
		1½-½	5009.5	.73	- .260	20%	
		1½-2½ ½-1½	4924.0 4925.3 }	.29	+ .023	20%	
8	4s ^4P - 4p $^2D^o$	2½-2½	4779.1	< .06	< - .909	----	
9*	4s ^4P - 4p $^4S^o$	2½-1½	4815.5	.78	+ .035	20%	
		1½-1½	4716.2	.26	- .460	20%	
		½-1½	4656.7	.16	- .682	35%	
10*	4s ^4P - 4p $^2P^o$	½-1½	4193.5	< .11	< - .936	----	
11	3d ^4F - 4p $^4D^o$	4½-3½	5606.1	.38	+ .156	20%	(2)
		2½-1½	5659.9	.45	- .063	20%	
		1½-½	5664.7	.52	- .301	20%	
		3½-3½	5526.2	.11	- .395	25%	
		2½-2½	5578.8	.10	- .553	20%	
		1½-1½	5616.6	.11	- .682	35%	
		1½-2½	5536.7	.09	- .605	30%	
		2½-3½ ?	5466.5	< .02	< -1.145	----	
14	4s ^2P - 4p $^2D^o$	1½-1½	5819.2	.11	- .651	40%	(3),(4)

(Table Continued)

*Measurement secured for all members of multiplet.

Remarks: (1) This transition measured absolutely: other S_{II} transitions are measured relative to it. (2) We omit λ5640.3 from this multiplet because of merging with λ5639.9 of multiplet #14. (3) From this multiplet we omit not only λ5639.9, as stated, but also 5645.9 which merges with 5645.6 of multiplet #6. (4) This transition is assigned a large tolerance because it was determined only twice.

Table 6. TRANSITION PROBABILITIES FOR S_{II} (Continued)

Multiplet	Transition (n, lower)(n, upper)	$J_n - J_m$	$\lambda(\mathring{A})$	A_{mn} $10^8 sec^{-1}$	$\log_{10} gf$	Tolerance	Remarks
15	$4s\ ^2P - 4p\ ^2P^\circ$	1½-1½	5014.0	.72	+ .036	±20%	
		½-½	4917.1	.42	- .516	25%	
32	$3d\ ^2P - 4p'\ ^2D^\circ$	1½-2½	4431.0	< .10	< - .75	----	(4)
36	$3d\ ^2D - 4p'\ ^2D^\circ$	2½-2½	4668.5	< .20	< - .41	----	(4)
		1½-1½	4648.1	< .30	< - .41	----	(4)
38*	$4s'\ ^2D - 4p'\ ^2F^\circ$	2½-3½	5320.7	1.05	+ .552	15%	
		1½-2½	5345.6	1.12	+ .459	15%	
39	$4s'\ ^2D - 4p'\ ^2D^\circ$	2½-2½	5212.6	.96	+ .370	20%	
		1½-1½ 2½-1½	5201.0 5201.3	.76	+ .091	20%	
40	$4s'\ ^2D - 4p'\ ^2F^\circ$	2½-1½ 1½-1½	4524.9 4524.6	1.04	+ .106	30%	
43	$4p\ ^4D^\circ - 5s\ ^4P$	3½-2½	4463.5	.74	+ .123	45%	(5)
		2½-1½	4483.4	.42	- .296	45%	
		1½-½	4486.6	.90	- .265	45%	
46	$4p\ ^4P^\circ - 5s\ ^4P$	2½-2½	4792.0	1.08	+ .348	30%	
49	$4p\ ^4P^\circ - 4d\ ^4D$	2½-3½	4294.4	< 1.0	< + .345	----	(4)
61	$4p\ ^2P^\circ - 5s\ ^2P$	½-½	5518.7	< 2.6	< + .376	----	(4)

*Measurement secured for all members of multiplet.

Remarks: (4) Upper limit estimates are given for lines which are detectable but not measurable to better than ±50 tolerance. (5) Large tolerance due to poor signal-to-noise ratio.