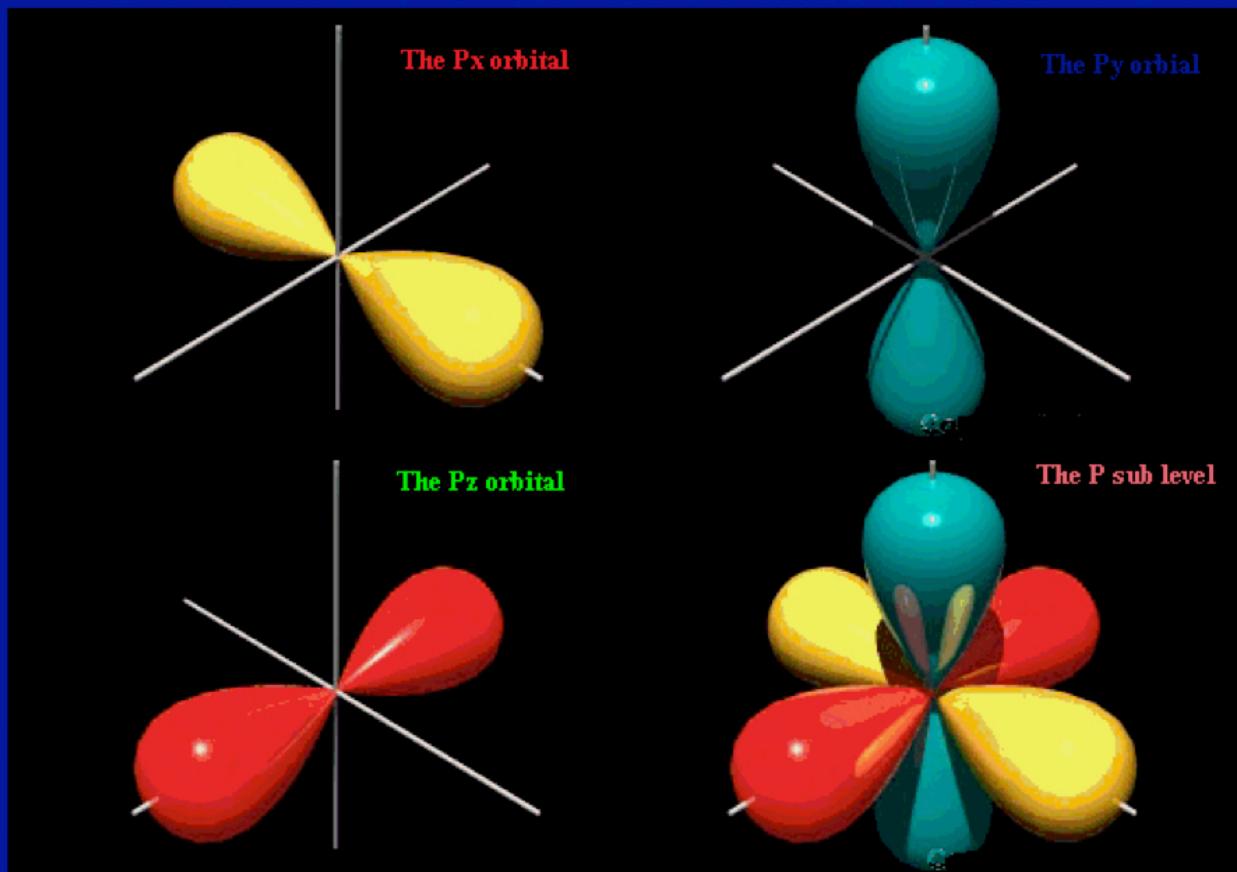


AST 515

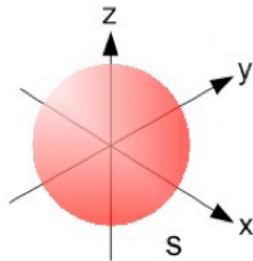
Atomic Spectroscopy



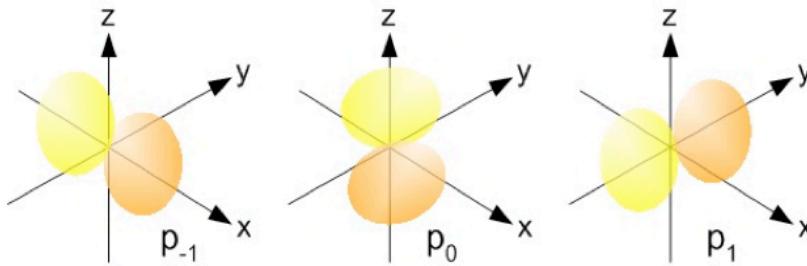
- Ionization indicated by Roman Numerals:
 - C_I is neutral Carbon (no ionization)
 - C_{II} is singly ionized (C^+)
 - C_{III} is doubly ionized (C^{++}) etc.
- Energy levels are expressed in many units:
 - $E = h\nu$ in units of ergs or eV
 - E/k has units of Temperature (K) [i.e. $E = kT$]
 - E/hc has units of cm^{-1} or wavenumber
 - To convert from cm^{-1} to K, multiply by $hc/k = 1.439$

Atomic Electron Orbitals

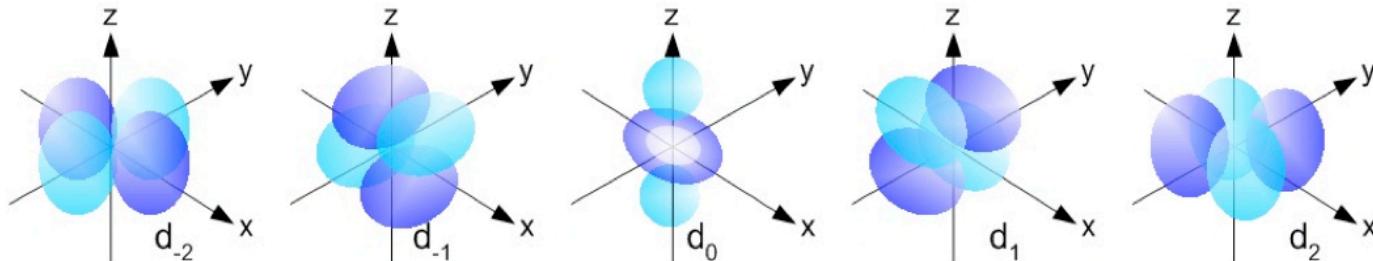
$|l = 0$



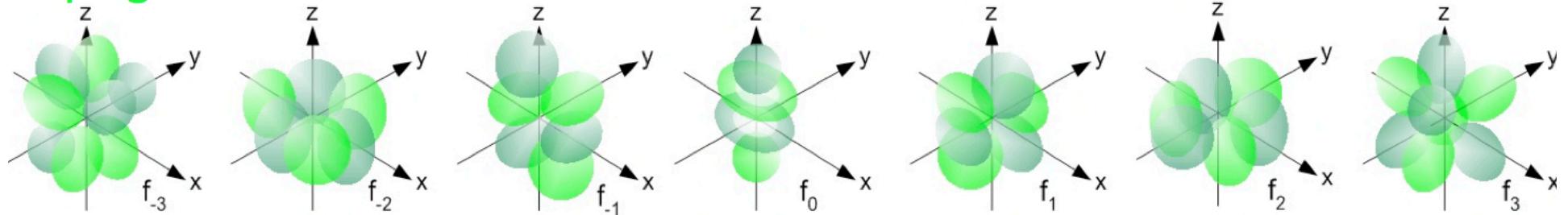
$|l = 1$



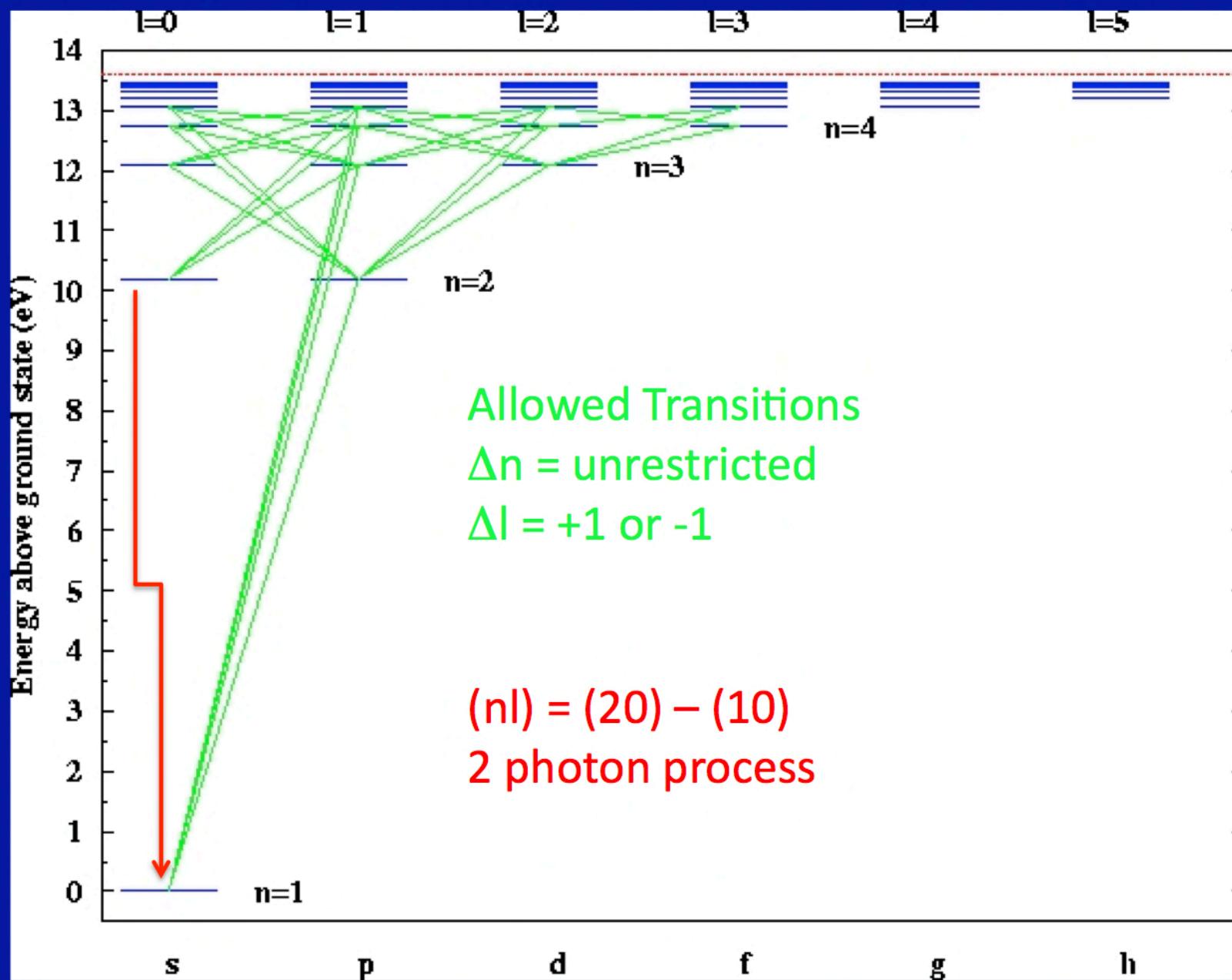
$|l = 2$



$|l = 3$



Hydrogen Grotrian Diagram



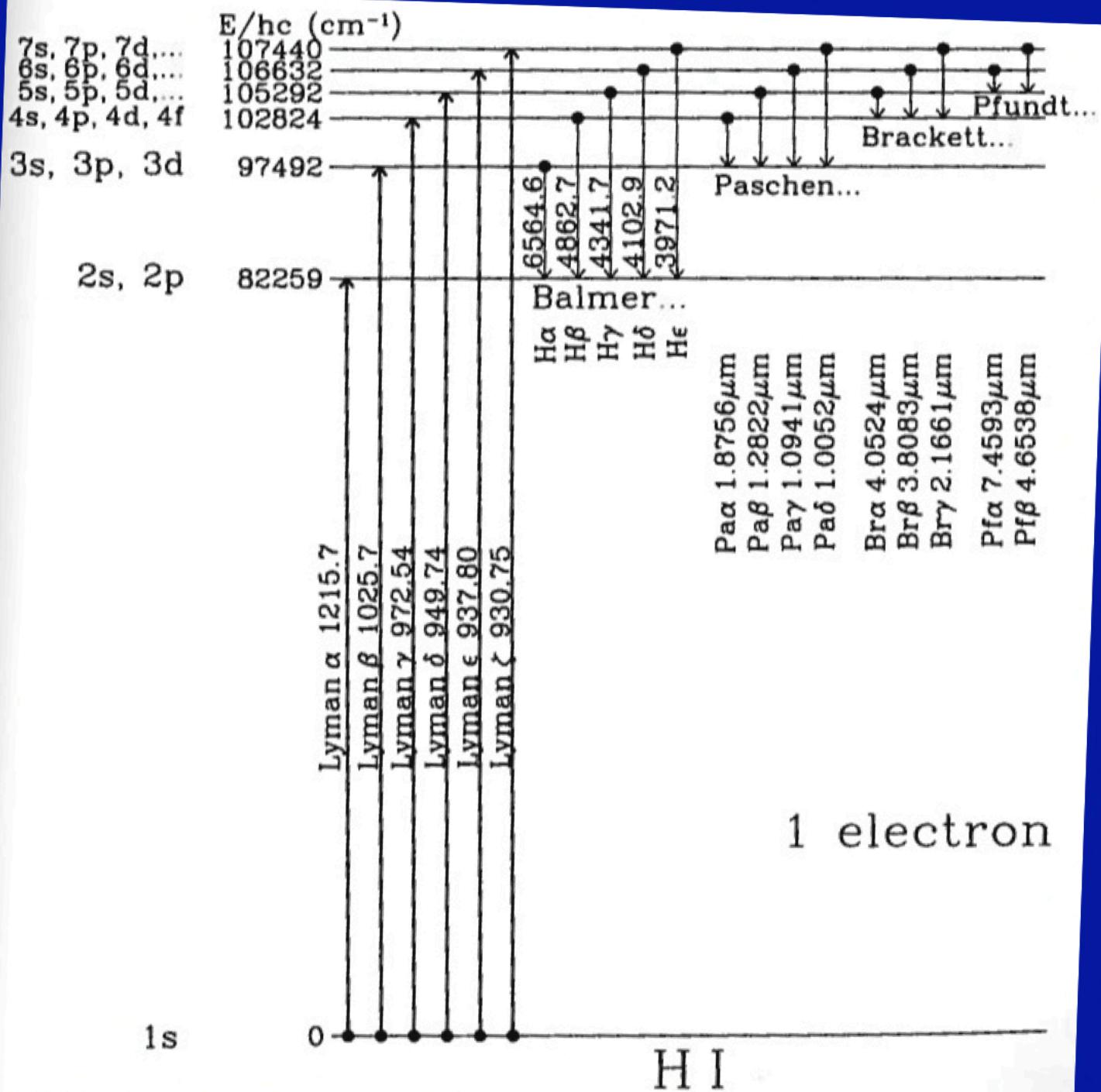


Table 9.1 Hydrogen Lyman Series

Transition	$\lambda(\text{\AA})$	$f_{\ell u}$	$A_{u,tot}(\text{s}^{-1})$
Ly $\alpha(1s - 2p)$	1215.67	0.4164	6.265×10^8
Ly $\beta(1s - 3p)$	1025.73	0.07912	1.672×10^8
Ly $\gamma(1s - 4p)$	972.54	0.02901	6.818×10^7
Ly $\delta(1s - 5p)$	949.74	0.01394	3.437×10^7
Ly $\epsilon(1s - 6p)$	937.80	0.007799	1.973×10^7
Ly $\zeta(1s - 7p)$	930.74	0.004184	1.074×10^7
Ly $\eta(1s - 8p)$	926.22	0.003183	8.249×10^6
Ly $\theta(1s - 9p)$	923.15	0.002216	5.781×10^6
Ly $\iota(1s - 10p)$	920.96	0.001605	4.209×10^6
Ly $(1s - np), n \gg 1$	$\frac{911.75}{1-n^2}$	$1.563n^{-3}$	$4.180 \times 10^9n^{-3}$

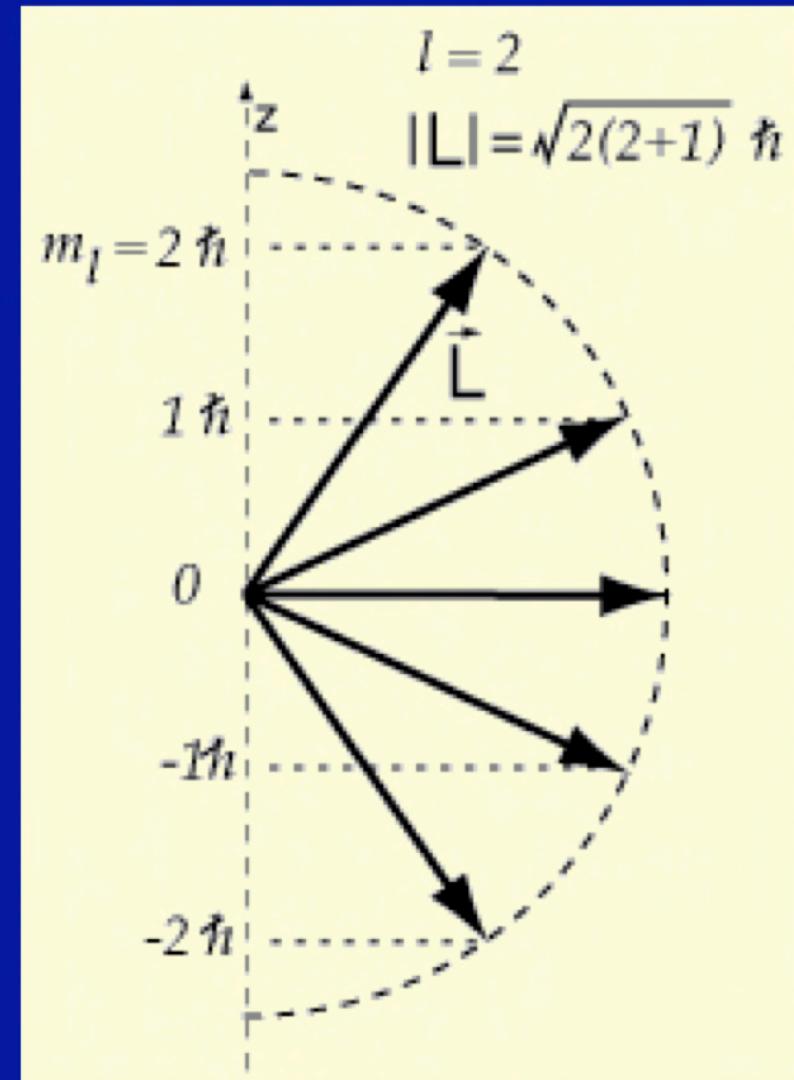
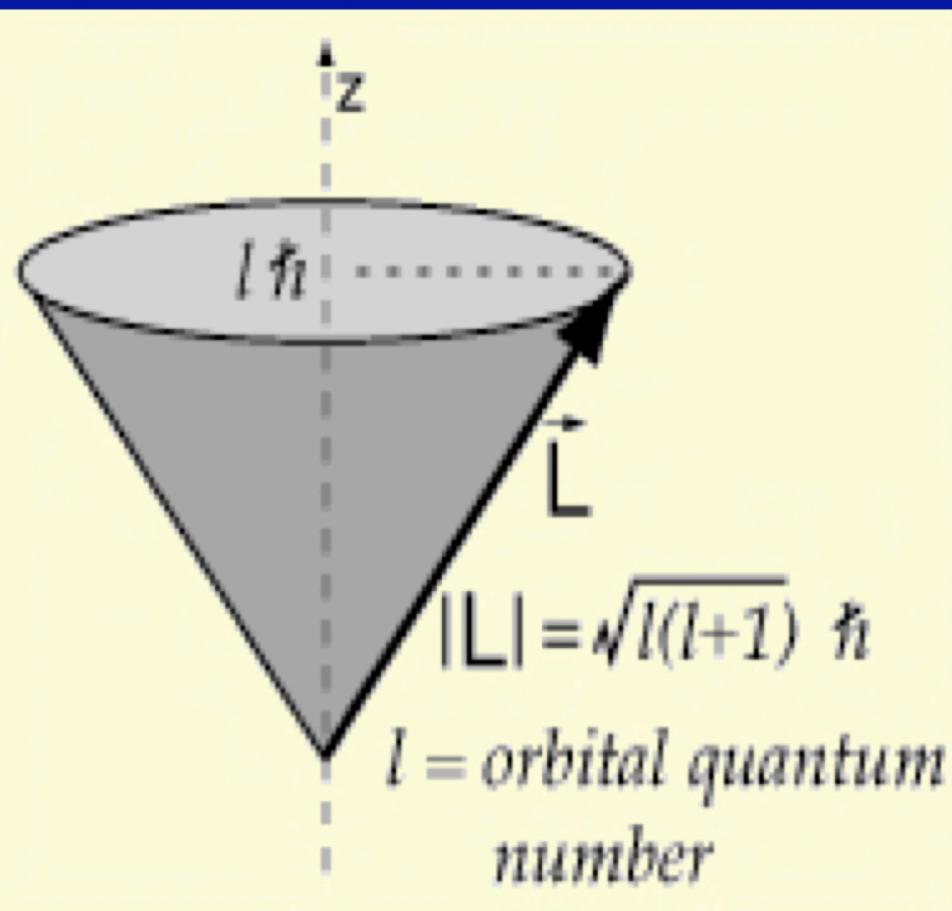
Electron Configurations in the Periodic Table

1 H 1s													2 He 1s				
3 Li 2s	4 Be																
11 Na 3s	12 Mg																
19 K 4s	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn						
37 Rb 5s	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
55 Cs 6s	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
87 Fr 7s	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110	111	112	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
						6d											

58 Ce ←	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu →
90 Th ←	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr →

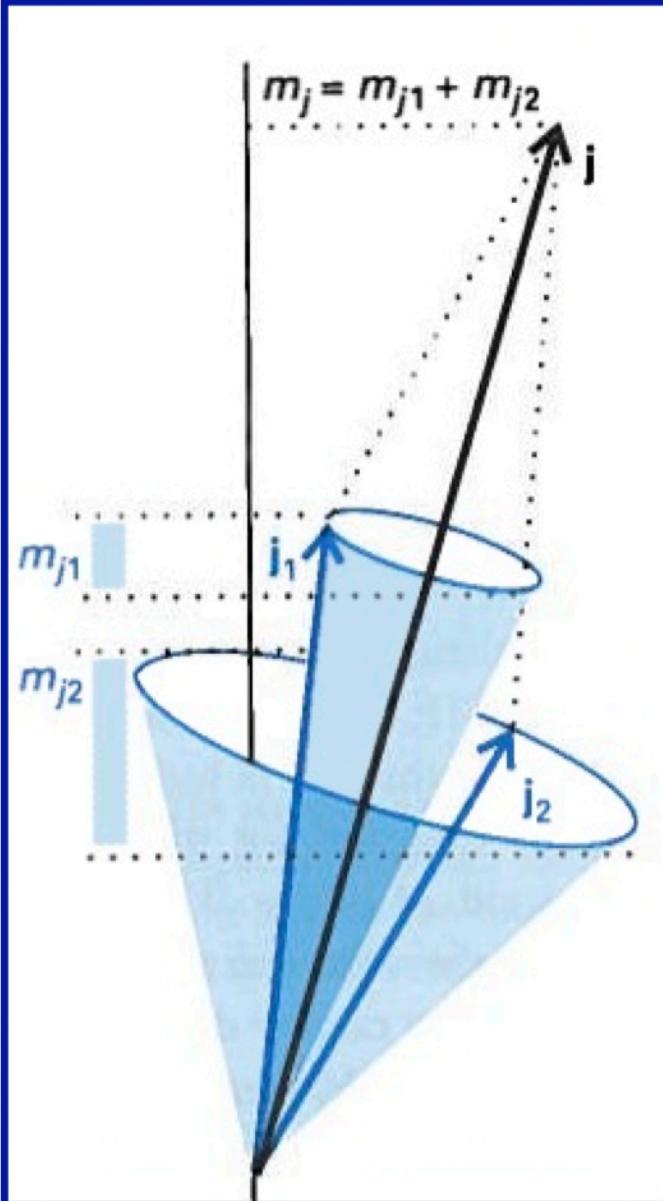
by: Sarah Faizi

Quantization of Angular Momentum



A precessing vector with quantized length and quantized projections on the space axis

Coupling Quantized Angular Momenta

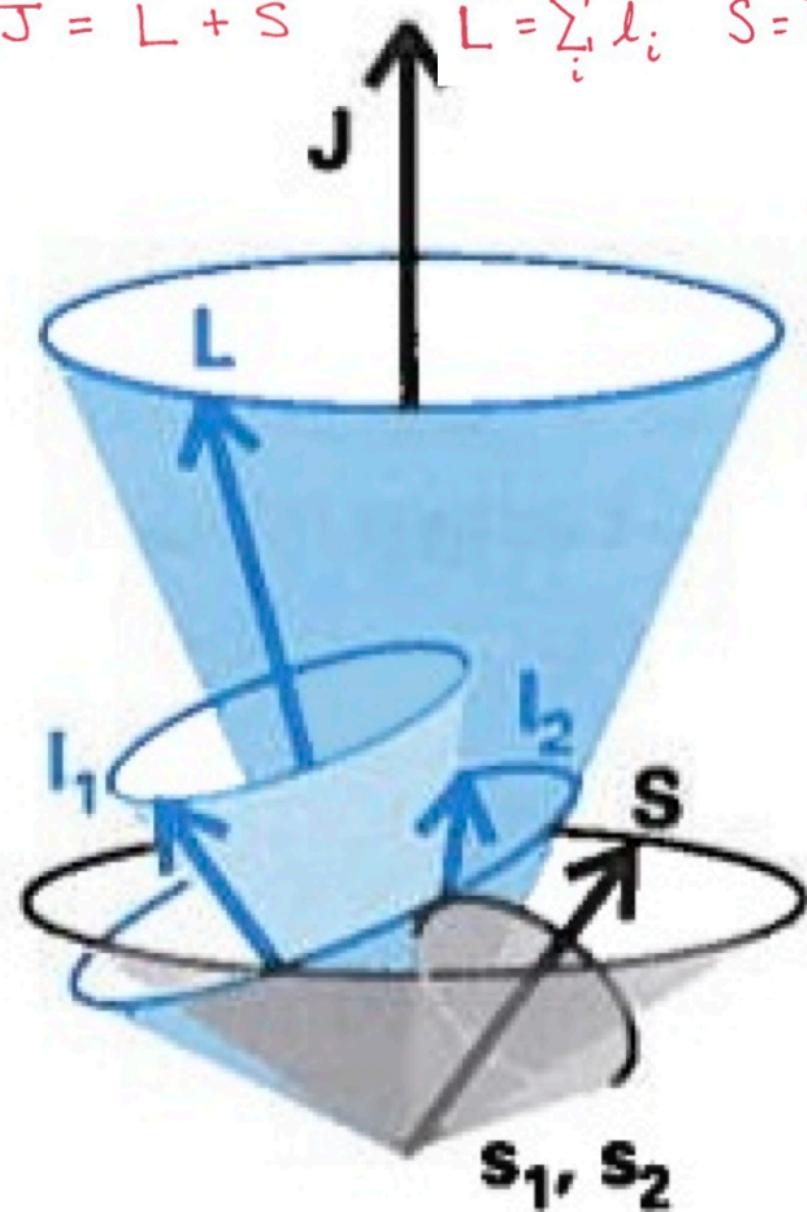


$$\vec{j} = \vec{j}_1 + \vec{j}_2$$
$$|\vec{j}| = j = |j_1 + j_2, j_1 + j_2 - 1, \dots, |j_1 - j_2|$$

- The length of the total angular momentum $j = [j(j+1)]^{1/2}$
- The j vector lies at an indeterminate angle on a cone about the z space axis
 - $j_1 = [j_1(j_1+1)]^{1/2}$ and
 - $j_2 = [j_2(j_2+1)]^{1/2}$
- The projections of j_1 and j_2 onto z are indefinite but $m_{j1} + m_{j2} = m_j$

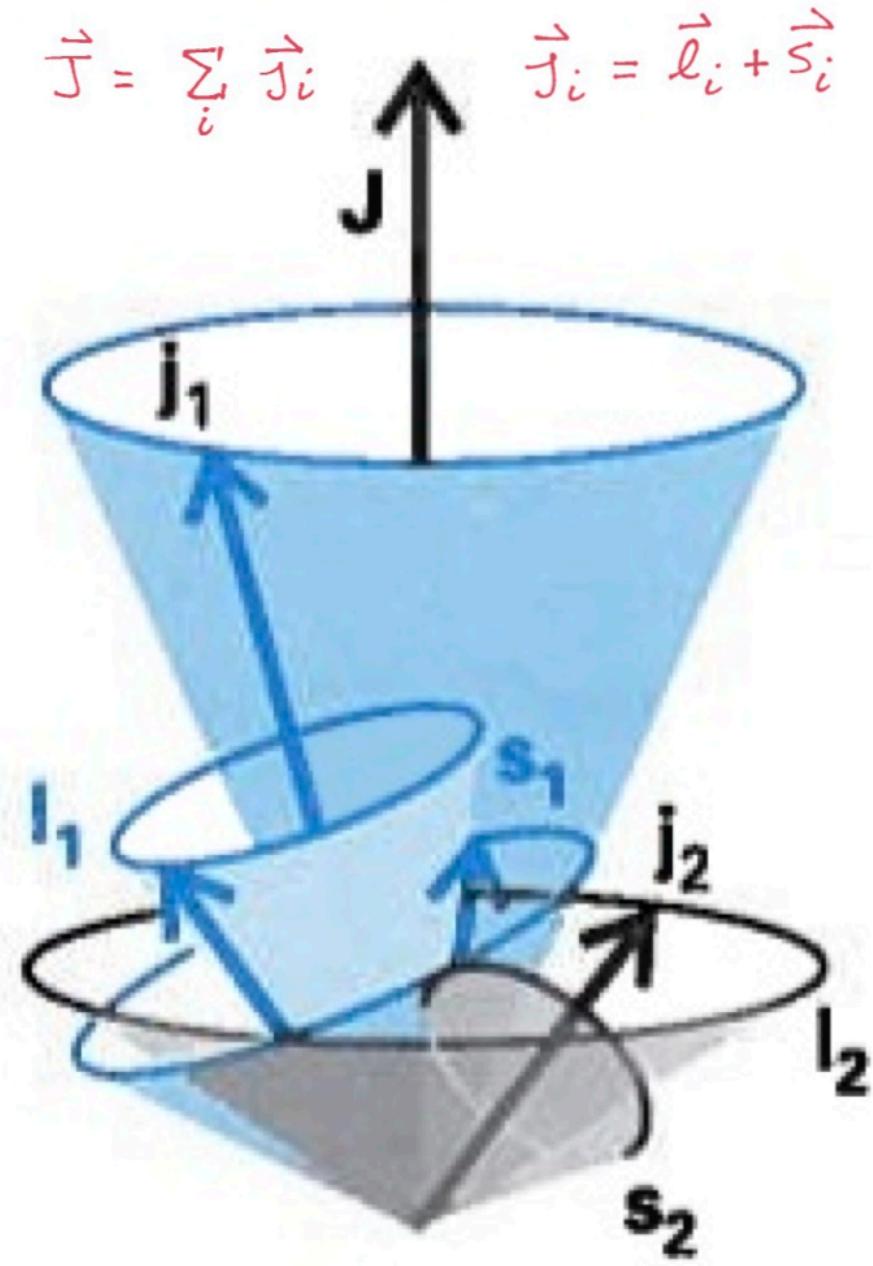
L S Coupling

$$\vec{J} = \vec{L} + \vec{S}$$



j j Coupling

$$\vec{J} = \sum_i \vec{j}_i$$



$$\vec{S} = \sum \vec{s}_i$$

Sum over
valence e^-
“Multiplicity”

$$\vec{L} = \sum \vec{l}_i$$

$L = 0 \rightarrow S$
 $L = 1 \rightarrow P$
 $L = 2 \rightarrow D$
 $L = 3 \rightarrow F$
 $L = 4 \rightarrow G$
etc.

$$2S+1$$

Parity = “e” if $\prod (-1)^{l_i} = +1$

Parity = “o” if $\prod (-1)^{l_i} = -1$

p

$$L_J$$

$$J = L+S, L+S-1, \dots, |L-S|$$

Parity Rules

Table 2.1
Parity Behavior for Multipole Operators

k	pole	Name	Parity	Parity
			Electric	Magnetic
1	2^1	dipole	odd	even
2	2^2	quadrupole	even	odd
3	2^3	octupole	odd	even

Table 2.2
Allowed Transition Multipoles

	Electric	Magnetic	Allowed k
Parity	must change	cannot change	$k = 1, 3, \dots$
Parity	cannot change	must change	$k = 2, 4, \dots$

Hund's Rules

- RULE 1: The term(s) arising from the ground electronic configuration with the maximum multiplicity ($2S+1$) lies lowest in energy
- RULE 2: Of several levels with the same multiplicity. The one with the maximum value of L lies lowest in energy
- RULE 3: Of several sublevels with the same multiplicity and total quantum number L:
 - (a) the sublevel with the minimum value of J lies lowest in energy if the configuration has a shell that is less than half-filled
 - (b) the sublevel with the maximum value of J lies lowest in energy if the configuration has a shell that is more than half-filled

TABLE 12.3 States allowed by the exclusion principle in the L-S coupling scheme

ns^0	1S				
ns^1		2S			
ns^2	1S		Highest E		Lowest E
np^0	1S				
np^1		2P			
np^2	$^1S, ^1D$		3P		
np^3		$^2P, ^2D$		4S	
np^4	$^1S, ^1D$		3P		
np^5		2P			
np^6	1S				
nd^0	1S				
nd^1		2D			
nd^2	$^1S, ^1D, ^1G$		$^3P, ^3F$		
nd^3		$^2D, ^2P, ^2D, ^2F, ^2G, ^2H$		$^4P, ^4F$	
nd^4	$^1S, ^1D, ^1G, ^1S, ^1D, ^1G, ^1F, ^1I$		$^3P, ^3F, ^3P, ^3D, ^3F, ^3G, ^3H$	5D	
nd^5		$^2D, ^2P, ^2D, ^2F, ^2G, ^2H, ^2S, ^2D, ^2F, ^2G, ^2I$		$^4P, ^4F, ^4D, ^4G$	6S
nd^6	$^1S, ^1D, ^1G, ^1S, ^1D, ^1G, ^1F, ^1I$		$^3P, ^3F, ^3P, ^3D, ^3F, ^3G, ^3H$	5D	
nd^7		$^2D, ^2P, ^2D, ^2F, ^2G, ^2H$		$^4P, ^4F$	
nd^8	$^1S, ^1D, ^1G$		$^3P, ^3F$		
nd^9		2D			
nd^{10}	1S				



TABLE 12.4 The periodic table

Group →

Period ↓

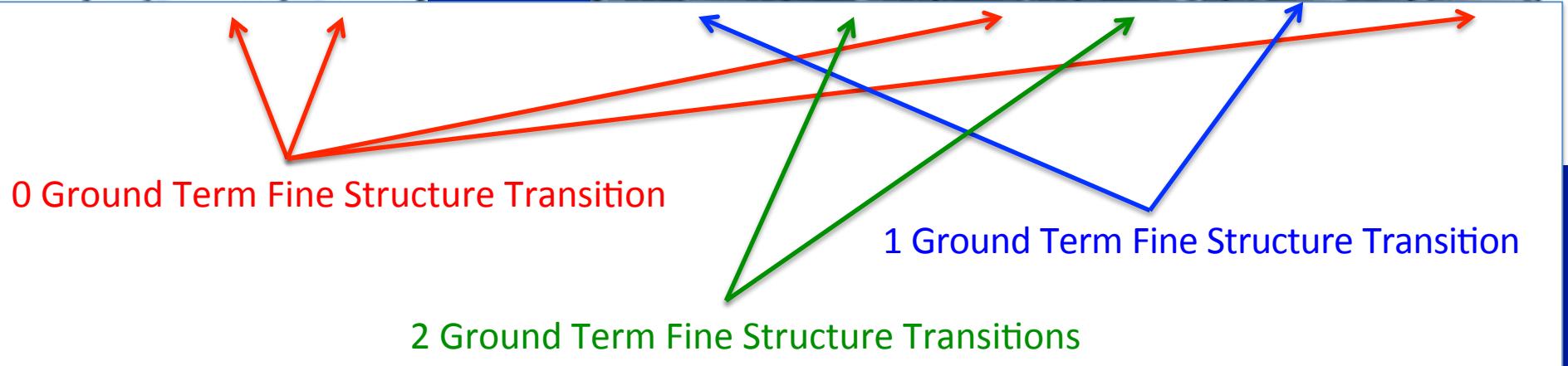
	I	II											III	IV	V	VI	VII	VIII		
I	H ¹ 1s ¹ ² S _{1/2}																He ² 1s ² ¹ S ₀			
2	Li ³ 1s ² 2s ¹ ² S _{1/2}	Be ⁴ 1s ² 2s ² ¹ S ₀											B ⁵ 2s ² 2p ¹ ² P _{1/2}	C ⁶ 2s ² 2p ² ³ P ₀	N ⁷ 2p ³ ⁴ S _{3/2}	O ⁸ 2p ⁴ ³ P ₂	F ⁹ 2p ⁵ ² P _{3/2}		Ne ¹⁰ 2p ⁶ ¹ S ₀	
3	Na ¹¹ 3s ¹ ² S _{1/2}	Mg ¹² 3s ² ¹ S ₀	Transition elements												Al ¹³ 3s ² 3p ¹ ² P _{1/2}	Si ¹⁴ 3s ² 3p ² ³ P ₀	P ¹⁵ 3p ³ ⁴ S _{3/2}	S ¹⁶ 3p ⁴ ³ P ₂	Cl ¹⁷ 3s ² 3p ⁵ ² P _{3/2}	Ar ¹⁸ 3s ² 3p ⁶ ¹ S ₀
4	K ¹⁹ 4s ¹ ² S _{1/2}	Ca ²⁰ 4s ² ¹ S ₀	Sc ²¹ 4s ² 3d ¹ ² D _{3/2}	Ti ²² 4s ² 3d ² ³ F ₂	V ²³ 4s ² 3d ³ ⁴ F _{3/2}	Cr ²⁴ 4s ¹ 3d ⁵ ⁷ S ₃	Mn ²⁵ 4s ² 3d ⁵ ⁶ S _{5/2}	Fe ²⁶ 4s ² 3d ⁶ ⁵ D ₄	Co ²⁷ 4s ² 3d ⁷ ⁴ F _{9/2}	Ni ²⁸ 4s ² 3d ⁸ ³ F ₄	Cu ²⁹ 4s ¹ 3d ¹⁰ ² S _{1/2}	Zn ³⁰ 4s ² 3d ¹⁰ ¹ S ₀	Ga ³¹ 4s ² 3d ¹⁰ 4p ¹ ² P _{1/2}	Ge ³² 3d ¹⁰ 4p ² ³ P ₀	As ³³ 3d ¹⁰ 4p ³ ⁴ S _{3/2}	Se ³⁴ 3d ¹⁰ 4p ⁴ ³ P ₂	Br ³⁵ 3d ¹⁰ 4p ⁵ ² P _{3/2}	Kr ³⁶ 4s ² 4p ⁶ ¹ S ₀		
5	Rb ³⁷ 5s ¹ ² S _{1/2}	Sr ³⁸ 5s ² ¹ S ₀	Y ³⁹ 5s ² 4d ¹ ² D _{3/2}	Zr ⁴⁰ 5s ² 4d ² ³ F ₂	Nb ⁴¹ 5s ¹ 4d ⁴ ⁶ D _{1/2}	Mo ⁴² 5s ¹ 4d ⁵ ⁷ S ₃	Tc ⁴³ 5s ² 4d ⁵ ⁶ S _{5/2}	Ru ⁴⁴ 5s ¹ 4d ⁷ ⁵ F ₅	Rh ⁴⁵ 5s ¹ 4d ⁸ ⁴ F _{9/2}	Pd ⁴⁶ 4d ¹⁰ ¹ S ₀	Ag ⁴⁷ 5s ¹ 4d ¹⁰ ² S _{1/2}	Cd ⁴⁸ 5s ² 4d ¹⁰ ¹ S ₀	In ⁴⁹ 5s ² 4d ¹⁰ 5p ¹ ² P _{1/2}	Sn ⁵⁰ 4d ¹⁰ 5p ² ³ P ₀	Sb ⁵¹ 4d ¹⁰ 5p ³ ⁴ S _{3/2}	Te ⁵² 4d ¹⁰ 5p ⁴ ³ P ₂	I ⁵³ 4d ¹⁰ 5p ⁵ ² P _{3/2}	Xe ⁵⁴ 5s ² 5p ⁶ ¹ S ₀		
6	Cs ⁵⁵ 6s ¹ ² S _{1/2}	Ba ⁵⁶ 6s ² ¹ S ₀	La ⁵⁷ 6s ² 5d ¹ ² D _{3/2}	Hf ⁷² 6s ² 5d ² ³ F ₂	Ta ⁷³ 6s ² 5d ³ ⁴ F _{3/2}	W ⁷⁴ 6s ² 5d ⁴ ⁵ D ₀	Re ⁷⁵ 6s ² 5d ⁵ ⁶ S _{5/2}	Os ⁷⁶ 6s ² 5d ⁶ ⁵ D ₄	Ir ⁷⁷ 6s ² 5d ⁷ ⁴ F _{9/2}	Pt ⁷⁸ 6s ¹ 5d ⁹ ³ D ₃	Au ⁷⁹ 6s ¹ 5d ¹⁰ ² S _{1/2}	Hg ⁸⁰ 6s ² 5d ¹⁰ ¹ S ₀	Tl ⁸¹ 6s ² 5d ¹⁰ 6p ¹ ² P _{1/2}	Pb ⁸² 6p ² ³ P ₀	Bi ⁸³ 6p ³ ⁴ S _{3/2}	Po ⁸⁴ 6p ⁴ ³ P ₂	At ⁸⁵ 6p ⁵ ² P _{3/2}	Rn ⁸⁶ 6p ⁶ ¹ S ₀		
7	Fr ⁸⁷ 7s ¹ ² S _{1/2}	Ra ⁸⁸ 7s ² ¹ S ₀	Ac ⁸⁹ 7s ² 6d ¹ ² D _{3/2}																	
Rare earths ^a			Ce ⁵⁸ 6s ² 5d ¹ 4f ¹ ³ H ₅	Pr ⁵⁹ 6s ² 4f ³ ⁴ I _{3/2}	Nd ⁶⁰ 6s ² 4f ⁴ ⁵ I ₄	Pm ⁶¹ 6s ² 4f ⁵ ⁶ H _{5/2}	Sm ⁶² 6s ² 4f ⁶ ⁷ F ₀	Eu ⁶³ 6s ² 4f ⁷ ⁸ S _{7/2}	Gd ⁶⁴ 6s ² 5d ¹ 4f ⁷ ⁹ D ₂	Tb ⁶⁵ 6s ² 5d ¹ 4f ⁸ ⁹ D ₃	Dy ⁶⁶ 6s ² 4f ¹⁰ ¹⁰ D ₄	Ho ⁶⁷ 6s ² 4f ¹¹ ¹¹ D ₅	Er ⁶⁸ 6s ² 4f ¹² ¹² F _{7/2}	Tm ⁶⁹ 6s ² 4f ¹³ ¹² F _{5/2}	Yb ⁷⁰ 6s ² 4f ¹⁴ ¹¹ S ₀	Lu ⁷¹ 6s ² 5d ¹ 4f ¹⁴ ² D _{3/2}				
Heavy elements ^b			Th ⁹⁰ 7s ² 6d ²	Pa ⁹¹ 6d ³	U ⁹² 6d ¹ 5f ³ ⁵ I ₄	Np ⁹³ 5f ⁵	Pu ⁹⁴ 5f ⁶	Am ⁹⁵ 5f ⁷ ⁸ S _{7/2}	Cm ⁹⁶ 6d ¹ 5f ⁷	Bk ⁹⁷ 5f ⁹	Cf ⁹⁸ 5f ¹⁰	E ⁹⁹ 5f ¹¹	Fm ¹⁰⁰ 5f ¹²	Md ¹⁰¹ 5f ¹³						

^a With La⁵⁷ included, this group is also called the *lanthanides*.^b With Ac⁸⁹ included, this group is also called the *actinides*.

TABLE I2.4 The periodic table

	Group →	Period ↓
	I	II
	$2S_{1/2}$	
I	H^1 $1s^1$ $2S_{1/2}$	$1S_0$
2	Li^3 $1s^2 2s^1$ $2S_{1/2}$	Be^4 $1s^2 2s^2$ $1S_0$
3	Na^{11} $3s^1$ $2S_{1/2}$	Mg^{12} $3s^2$ $1S_0$

Ground Electronic Terms							
III	IV	V	VI	VII	VIII		
$2P_{1/2}$	$3P_0$	$4S_{3/2}$	$3P_2$	$2P_{3/2}$		He^2 $1s^2$ $1S_0$	
B^5 $2s^2 2p^1$ $2P_{1/2}$	C^6 $2s^2 2p^2$ $3P_0$	N^7 $2p^3$ $4S_{3/2}$	O^8 $2p^4$ $3P_2$	F^9 $2p^5$ $2P_{3/2}$		Ne^{10} $2p^6$ $1S_0$	
Al^{13} $3s^2 3p^1$ $2P_{1/2}$	Si^{14} $3s^2 3p^2$ $3P_0$	P^{15} $3p^3$ $4S_{3/2}$	S^{16} $3p^4$ $3P_2$	Cl^{17} $3p^5$ $2P_{3/2}$		Ar^{18} $3s^2 3p^6$ $1S_0$	



FINE Structure Periodic Table

BI	CI	NI	OI	FI
$2P_{3/2}$ 655.6 μm $2P_{1/2}$	$3P_2$ 370.4 μm $3P_1$ 609.4 μm $3P_0$	$4S_{3/2}$ X	$3P_0$ 145.5 μm $3P_1$ 63.2 μm $3P_2$	$2P_{1/2}$ 24.7 μm $2P_{3/2}$
C II	N II	O II	F II	Ne II
$2P_{3/2}$ 157.7 μm $2P_{1/2}$	$3P_2$ 121.9 μm $3P_1$ 205.5 μm $3P_0$	$4S_{3/2}$ X	$3P_0$ 67.2 μm $3P_1$ 29.3 μm $3P_2$	$2P_{1/2}$ 12.8 μm $2P_{3/2}$
Al I	Si I	P I	SI	Cl I
$2P_{3/2}$ 89.2 μm $2P_{1/2}$	$3P_2$ 68.5 μm $3P_1$ 129.7 μm $3P_0$	$4S_{3/2}$ X	$3P_0$ 56.3 μm $3P_1$ 25.2 μm $3P_2$	$2P_{1/2}$ 11.3 μm $2P_{3/2}$
Si II	P II	S II	Cl II	Ar II
$2P_{3/2}$ 34.8 μm $2P_{1/2}$	$3P_2$ 32.9 μm $3P_1$ 60.6 μm $3P_0$	$4S_{3/2}$ X	$3P_0$ 33.3 μm $3P_1$ 14.4 μm $3P_2$	$2P_{1/2}$ 6.99 μm $2P_{3/2}$

Selection Rules – Electric Dipole Transitions

“Resonance Lines”

- (1) Parity must change $e \rightarrow o$ or $o \rightarrow e$
- (2) $\Delta L = 0, +1, -1$
- (3) $\Delta J = 0, +1, -1$ but $0 \not\rightarrow 0$
- (4) Only a single e^- wavefunction nl changes with $\Delta l = +1$ or -1
- (5) $\Delta S = 0$

Table 9.3 Selected^a Resonance Lines^b with $\lambda > 3300 \text{ \AA}$, $f_{\ell u} > 0.015$

	Configurations	ℓ	u	$E_{\ell}/hc (\text{ cm}^{-1})$	$\lambda_{\text{vac}} (\text{\AA})$	$f_{\ell u}$	Note
Na I	$2p^6 3s - 2p^6 3p$	$^2S_{1/2}$	$^2P_{3/2}^o$	0	5891.582	0.641	Na D ₂
		$^2S_{1/2}$	$^2P_{1/2}^o$	0	5897.558	0.320	Na D ₁
Al I	$3s^2 3p - 3s^2 4s$	$^2P_{1/2}^o$	$^2S_{1/2}$	0	3945.122	0.115	
		$^2P_{3/2}^o$	$^2S_{3/2}$	112.06	3962.641	0.12	
K I	$3p^6 4s - 3p^6 4p$	$^2S_{1/2}$	$^2P_{3/2}^o$	0	7667.01	0.682	
		$^2S_{1/2}$	$^2P_{1/2}^o$	0	7701.08	0.340	
Ca I	$3p^6 4s^2 - 3p^6 4s4p$	1S_0	$^1P_1^o$	0	4227.918	1.750	
Ca II	$3p^6 4s - 3p^6 4p$	$^2S_{1/2}$	$^2P_{3/2}^o$	0	3934.77	0.682	Ca II K
		$^2S_{1/2}$	$^2P_{1/2}^o$	0	3969.59	0.33	Ca II H

Table 9.4 Selected Resonance Lines^a with $\lambda < 3000 \text{ \AA}$

Cl	$2s^2 2p^2 - 2s^2 2p3s$	3P_0	$^3P_1^o$	0	1656.928	0.140	
		3P_1	$^3P_2^o$	16.40	1656.267	0.0588	
		3P_2	$^3P_2^o$	43.40	1657.008	0.104	
N II	$2s^2 2p^2 - 2s2p^3$	3P_0	$^3D_1^o$	0	1083.990	0.115	
		3P_1	$^3D_2^o$	48.7	1084.580	0.0861	
		3P_2	$^3D_3^o$	130.8	1085.701	0.0957	
Ni	$2s^2 2p^3 - 2s^2 2p^2 3s$	$^4S_{3/2}^o$	$^4P_{5/2}$	0	1199.550	0.130	
		$^4S_{3/2}^o$	$^4P_{3/2}$	0	1200.223	0.0862	
O I	$2s^2 2p^4 - 2s^2 2p^3 3s$	3P_2	$^3S_1^o$	0	1302.168	0.0520	
		3P_1	$^3S_1^o$	158.265	1304.858	0.0518	
		3P_0	$^3S_1^o$	226.977	1306.029	0.0519	

Forbidden Transitions

- (1) Semi – Forbidden (or Spin Forbidden) or Intersystem Transition
 - ΔS not equal to 0
 - Notation is single rightside bracket : NII]2143.4 Å
- (2) Forbidden Transition
 - Any transitions that fails any one of rules 1-4 for electric dipole transitions
 - Parity does not change for magnetic dipole or electric quadrupole transitions
 - Notation is full square brackets: [NII] 6549.4 Å
 - Fine structure lines are forbidden transitions
 - e.g. NII 205 um or 122 um

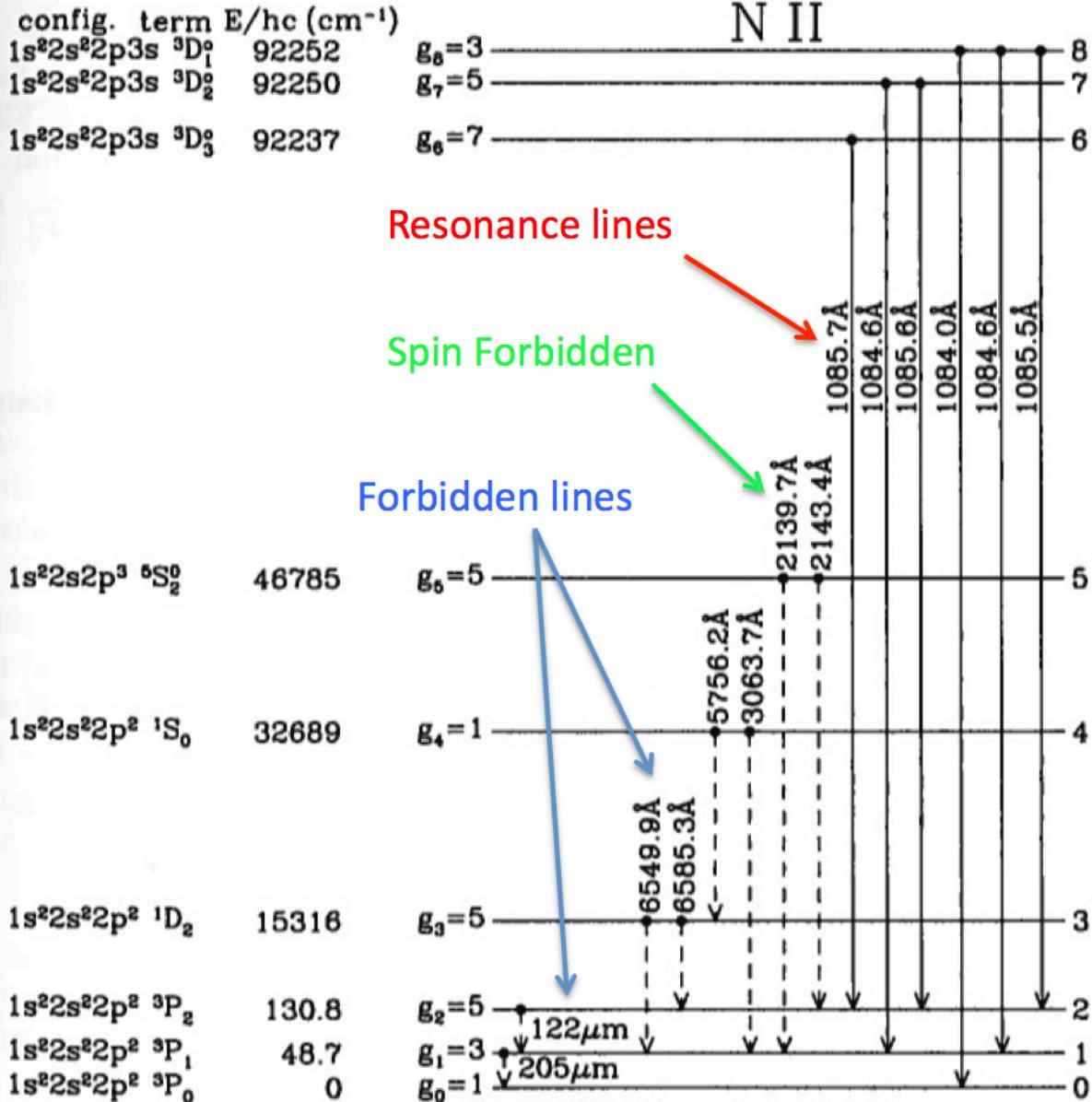


Figure 6.1 First nine energy levels of N II. Forbidden transitions are indicated by broken lines, and allowed transitions by solid lines; forbidden decays are not shown from levels that have permitted decay channels. Fine-structure splitting is not to scale. Hyperfine splitting is not shown.

Helium

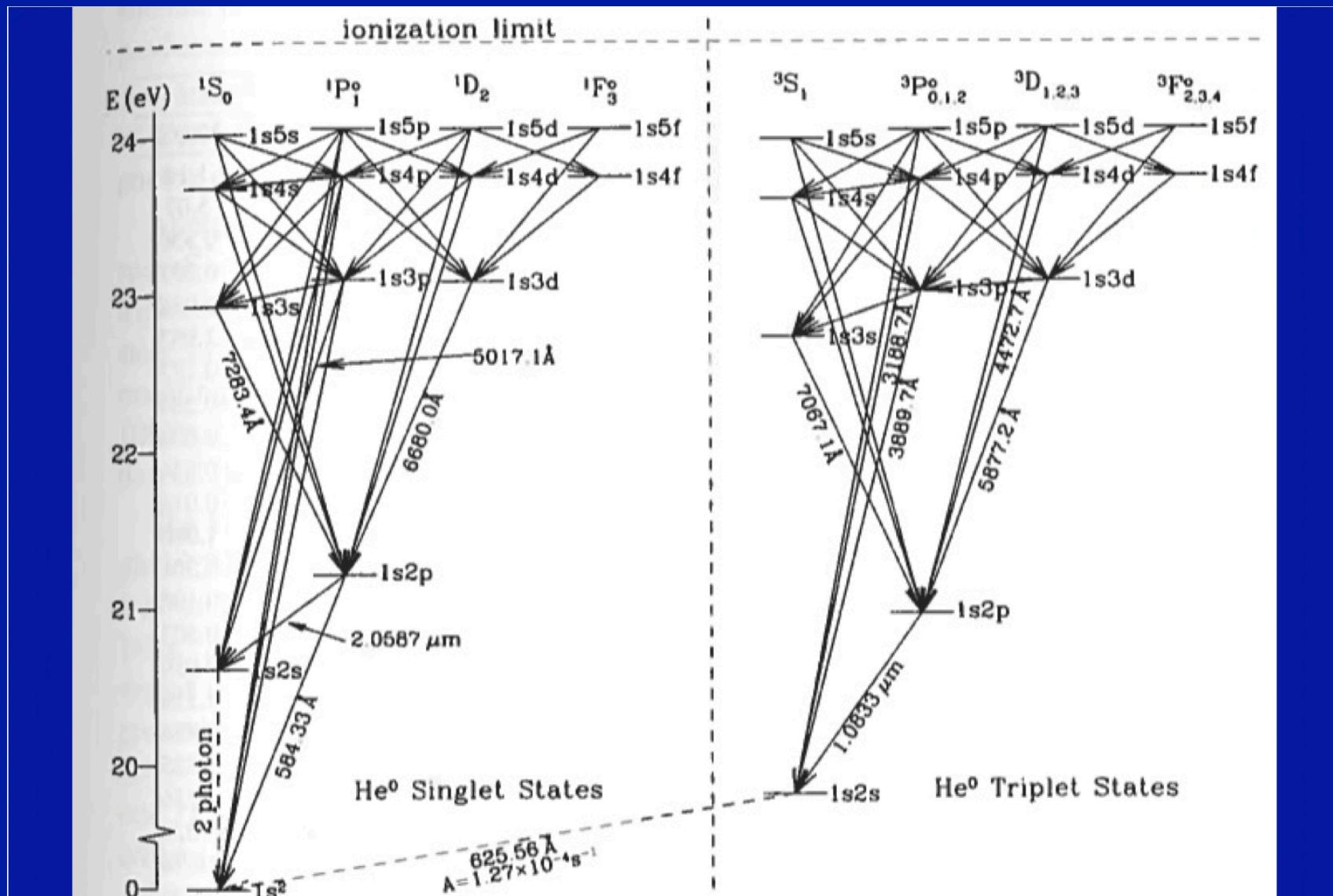
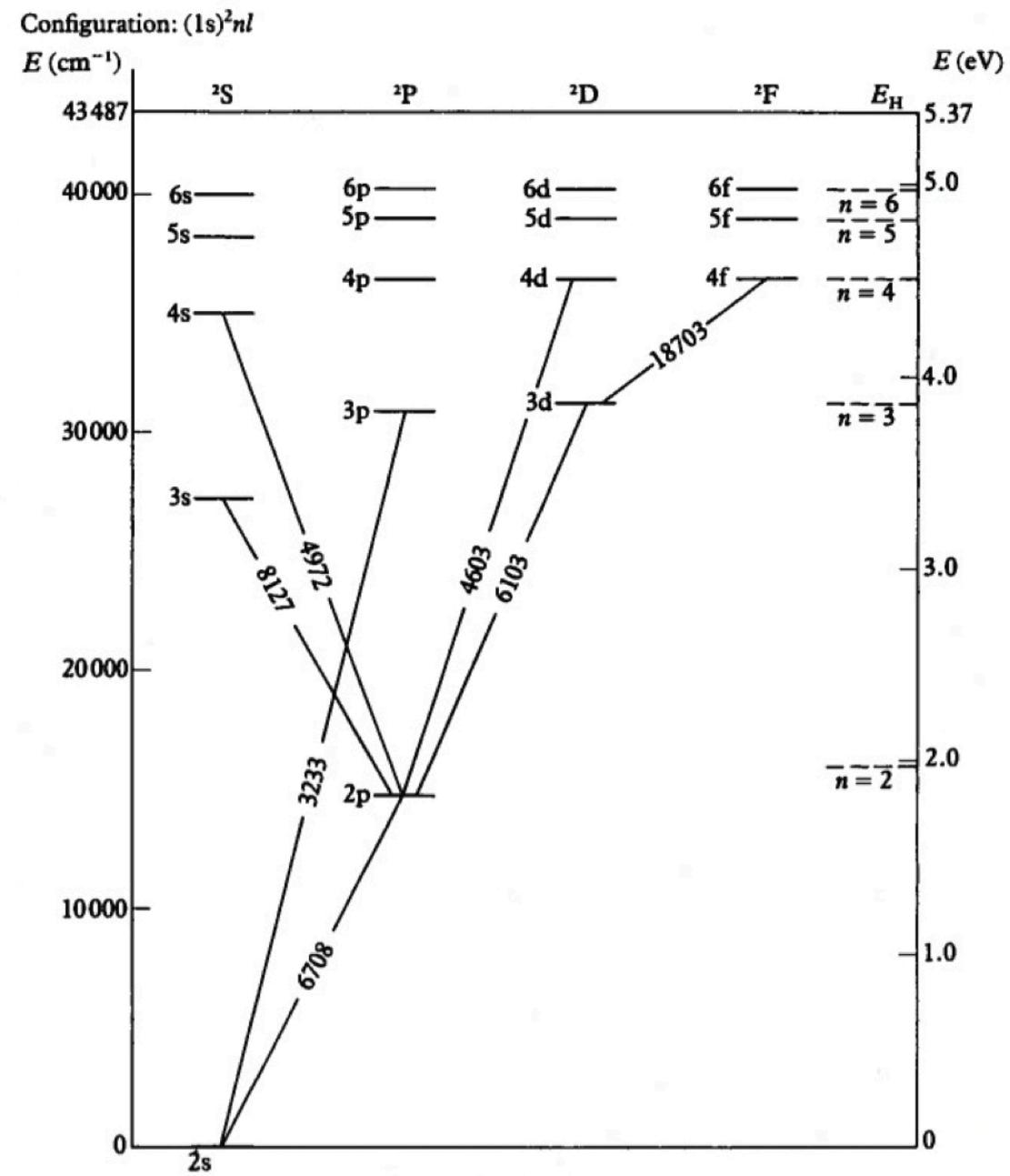


Figure 14.3 Radiative decay pathways for He⁰ (see text). Selected lines are labeled by vacuum wavelength.

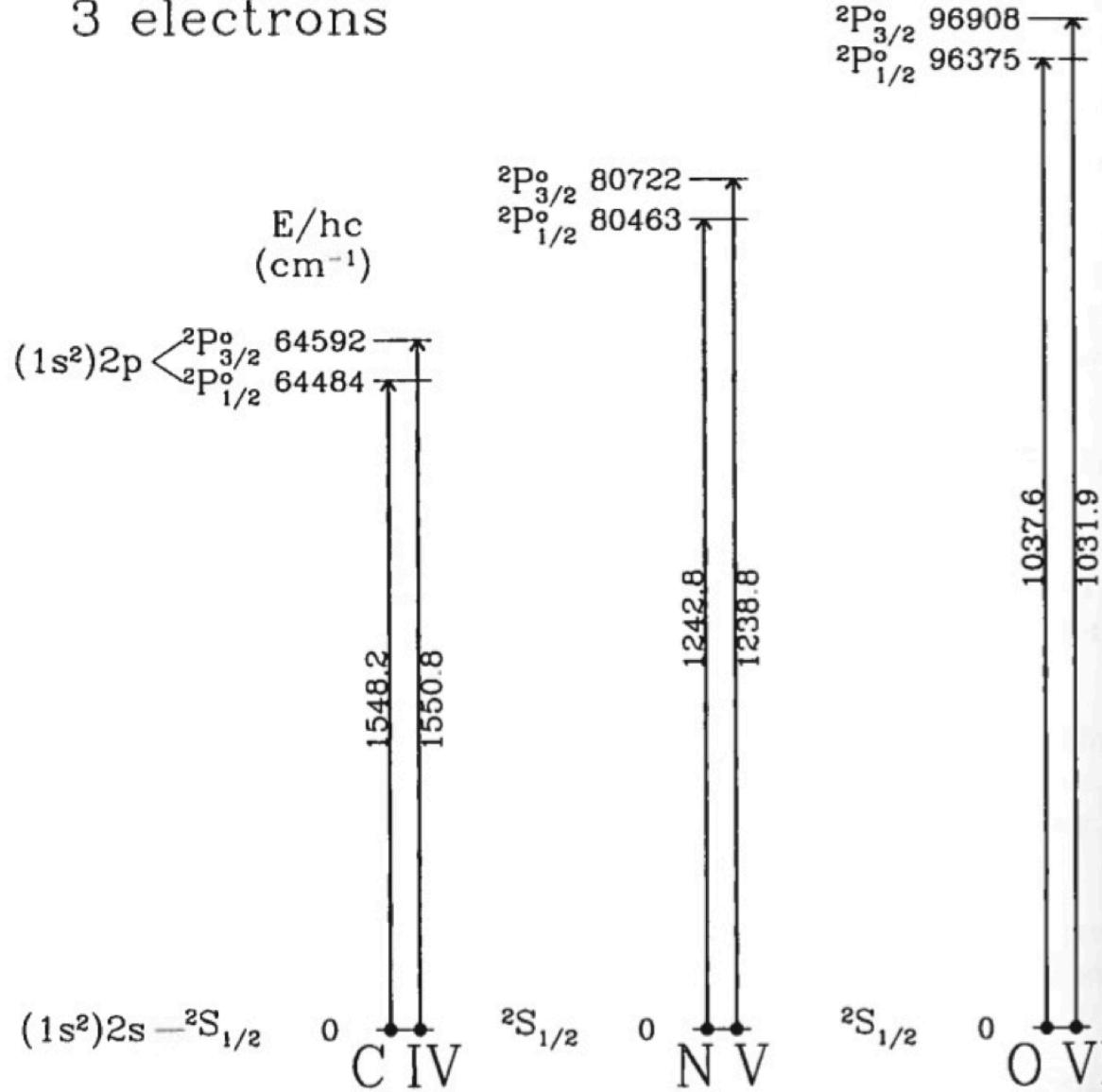
Lithium



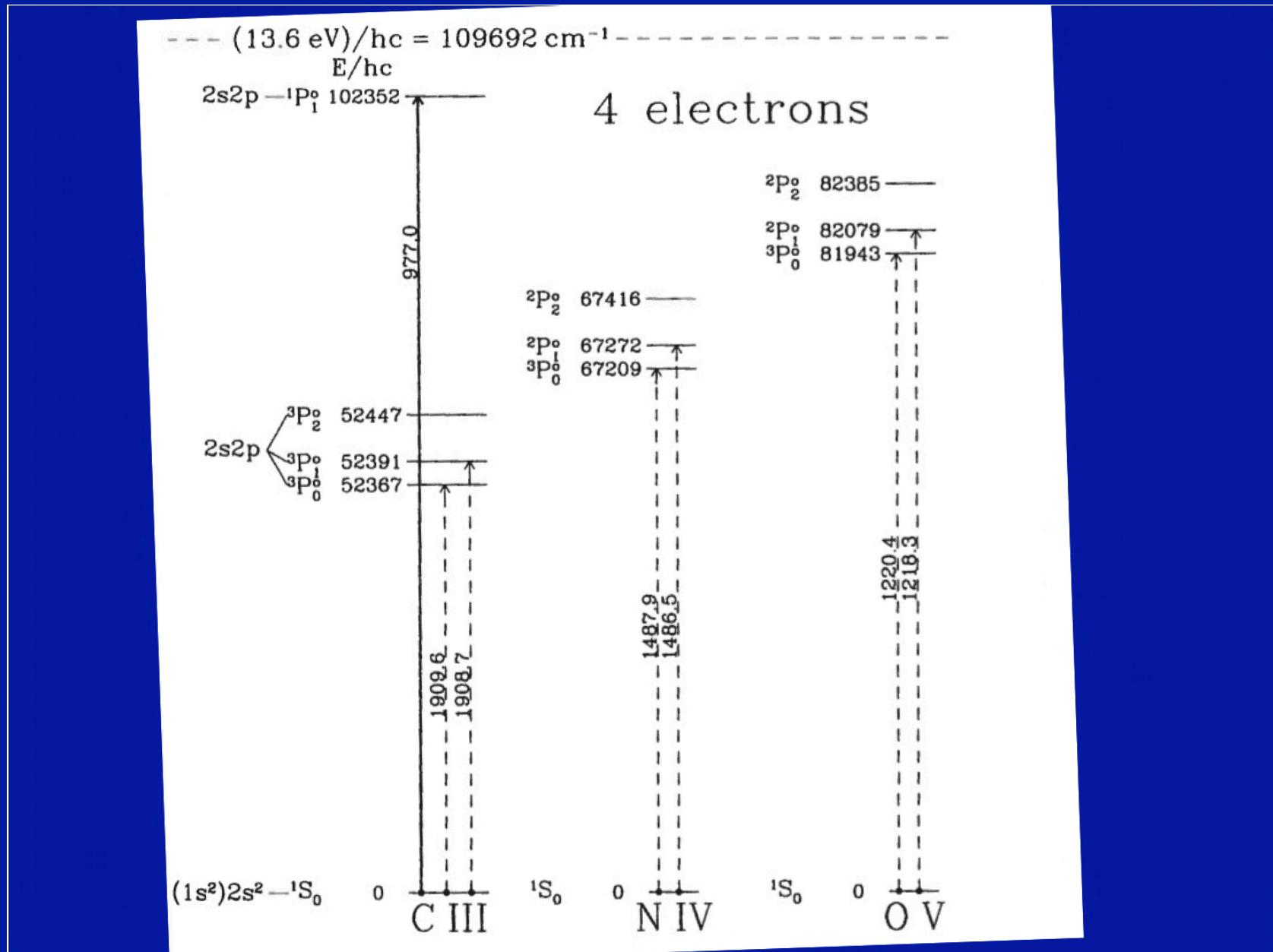
Lithium-like ions

$$--- \quad (13.6 \text{ eV})/\hbar c = 109692 \text{ cm}^{-1} \quad -----$$

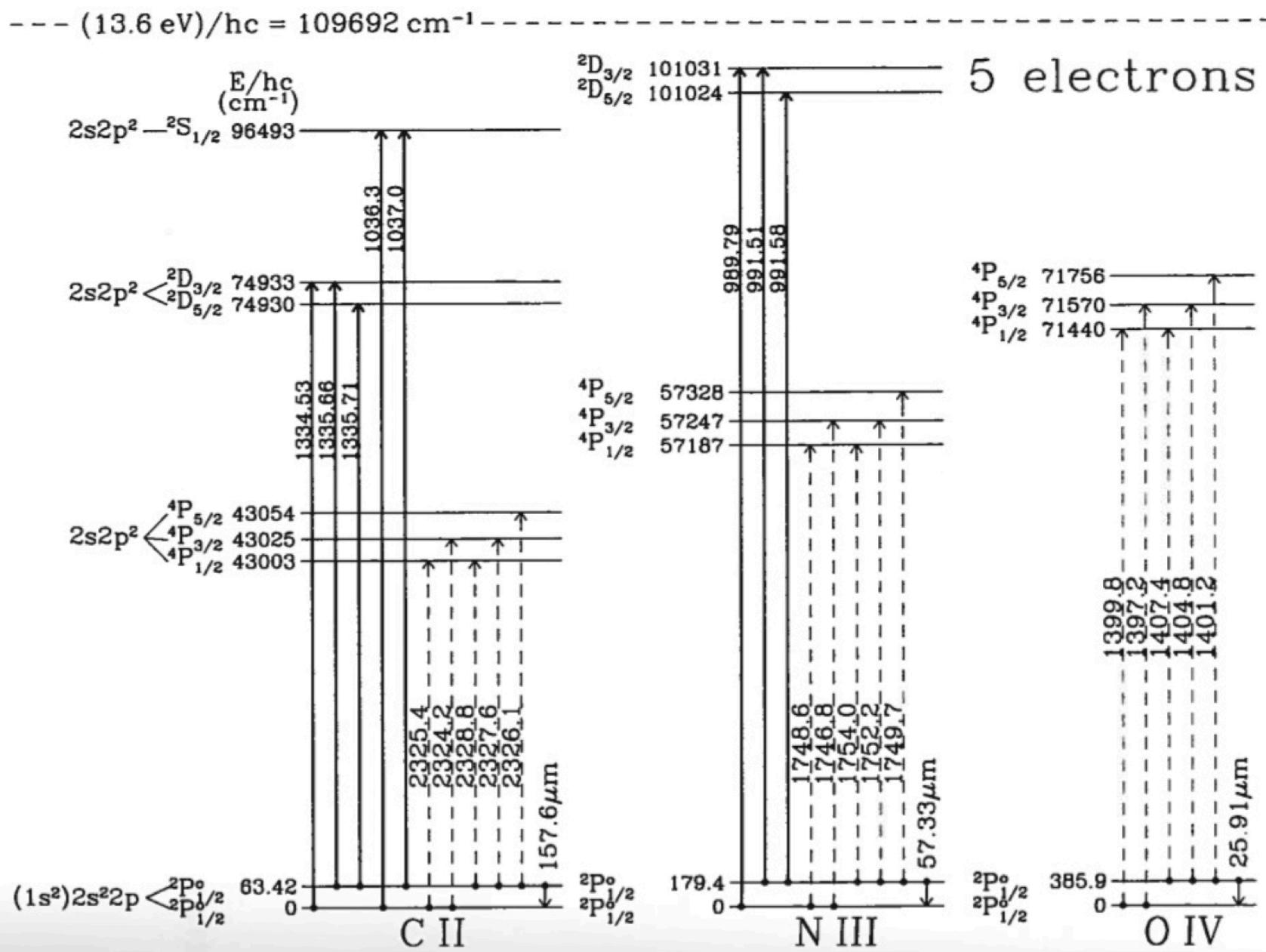
3 electrons



Beryllium-like ions



Boron-like ions

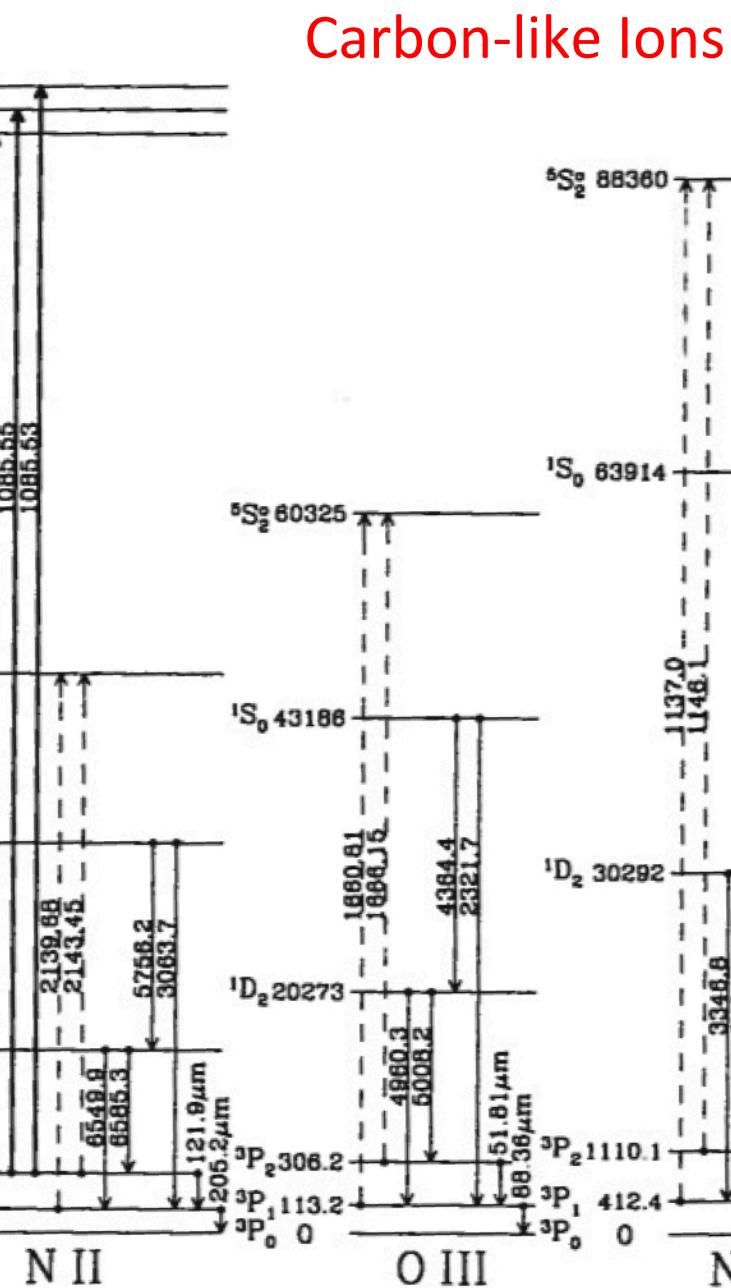
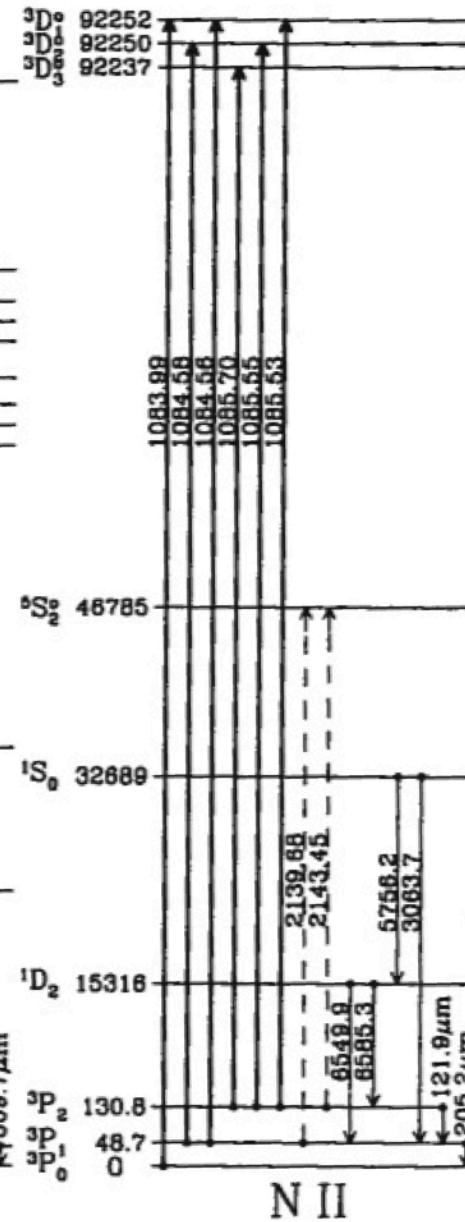
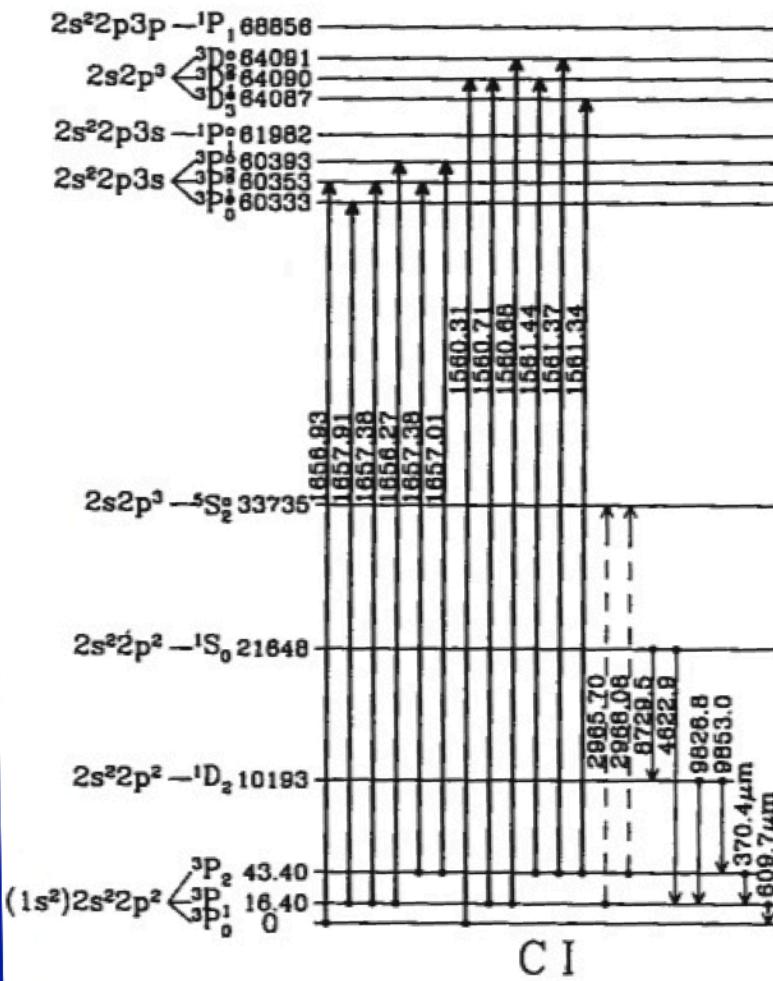


--- (13.6 eV)/hc = 109692 cm⁻¹ ---

^{3P₂} 109224
^{3P₁} 109218
^{3P₀} 109217

6 electrons

E/hc
(cm⁻¹)
IONIZATION 90820



Carbon-like Ions

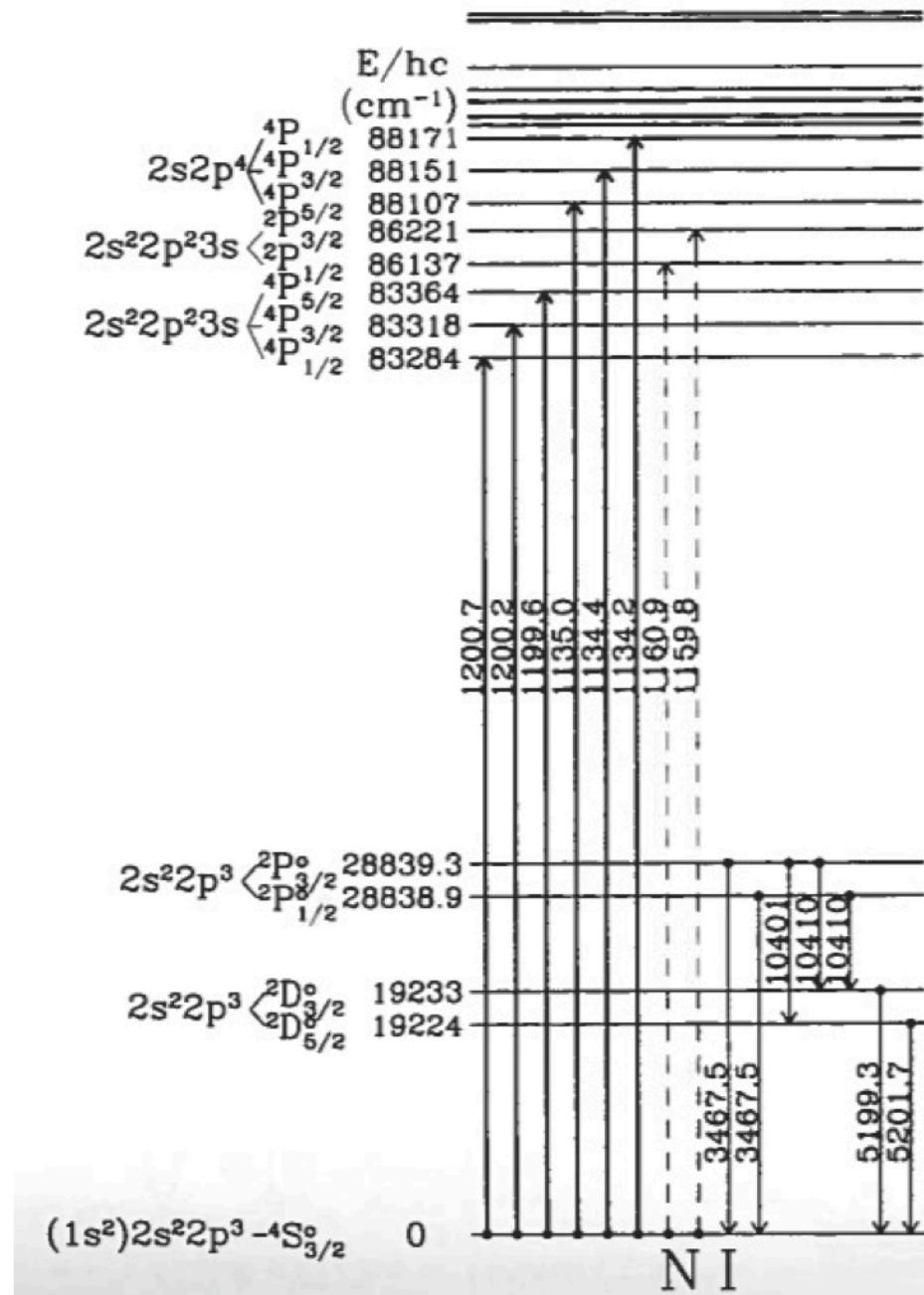
Ne V

3346.8
3426.6
14.33 μm
24.27 μm

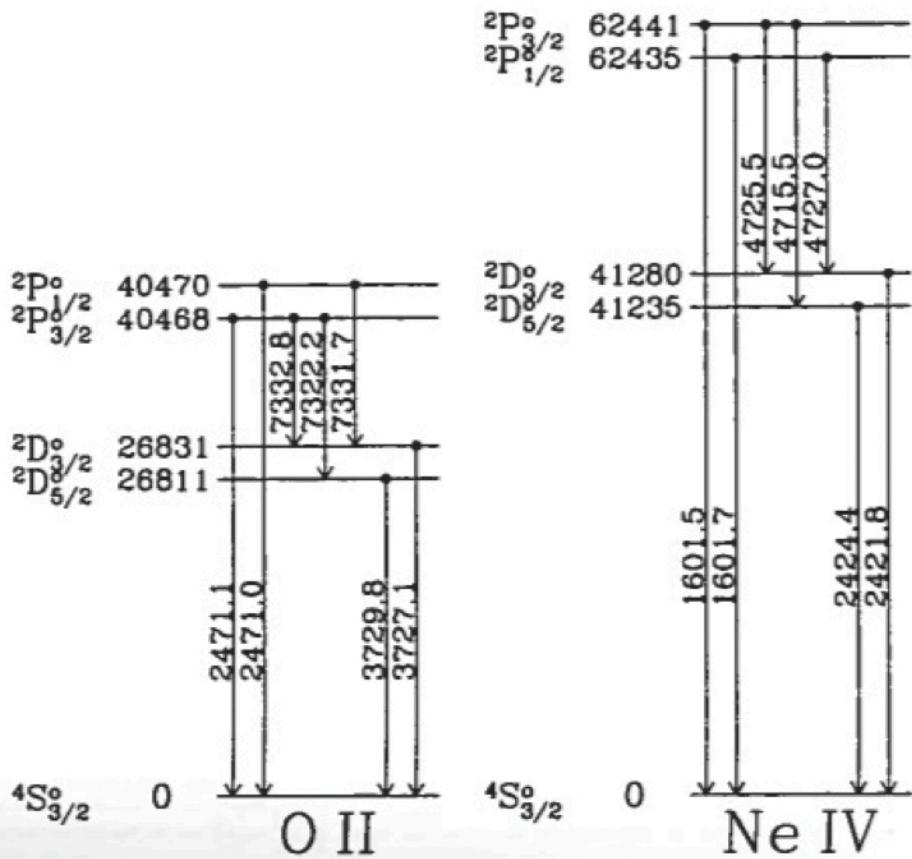
1137.9
1146.1
2874.2
1574.8

5S₂ 60325, ^{1S₀} 1880.81, ^{1D₂} 4364.4, ^{1D₂} 2321.7

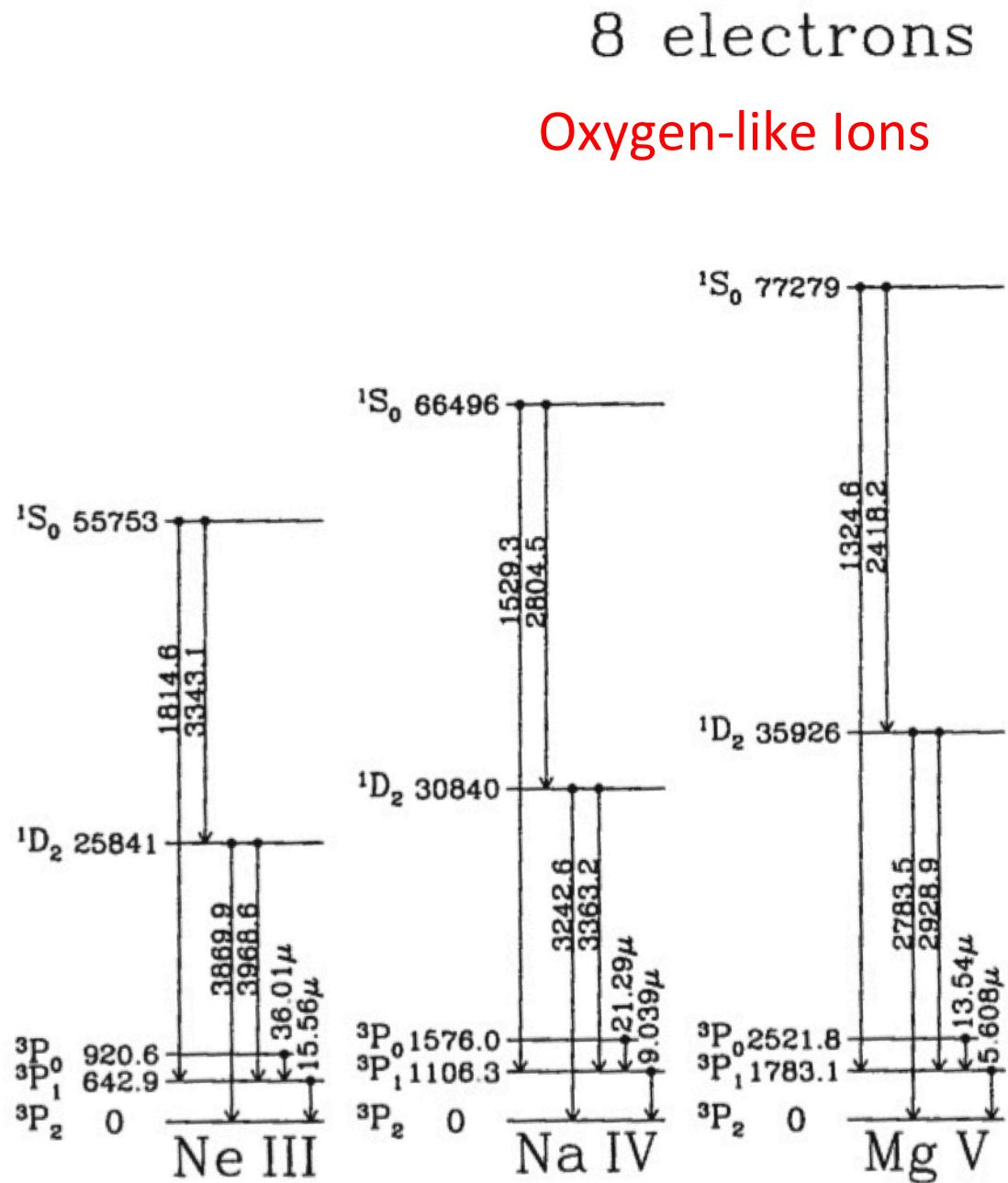
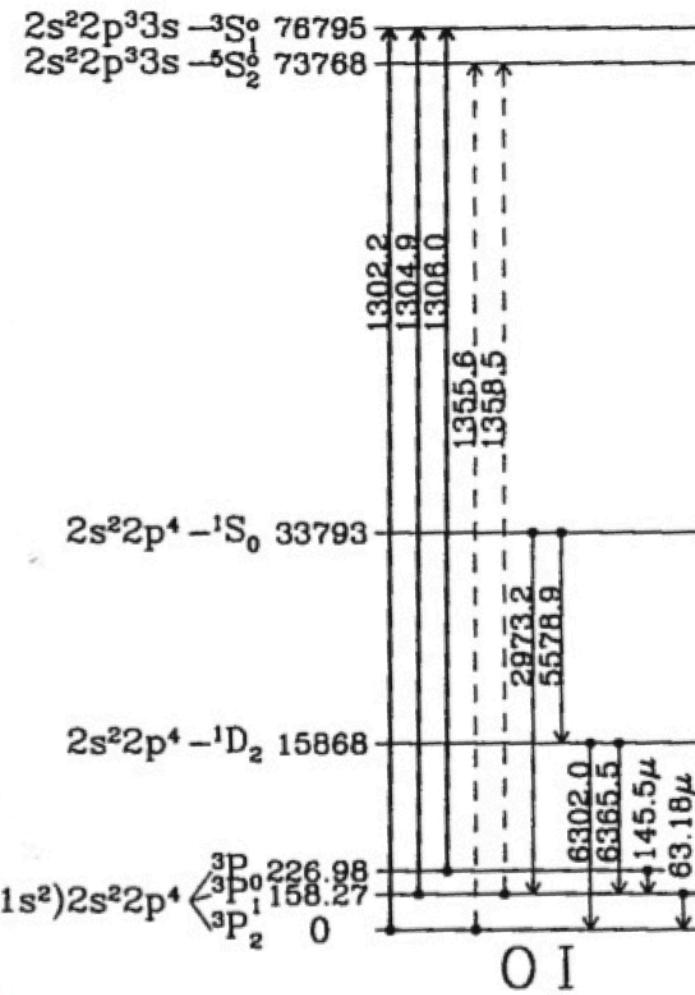
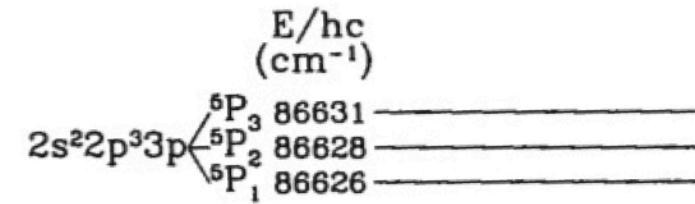
--- (13.6 eV)/hc = 109692 cm⁻¹ -----



7 electrons
Nitrogen-like ions



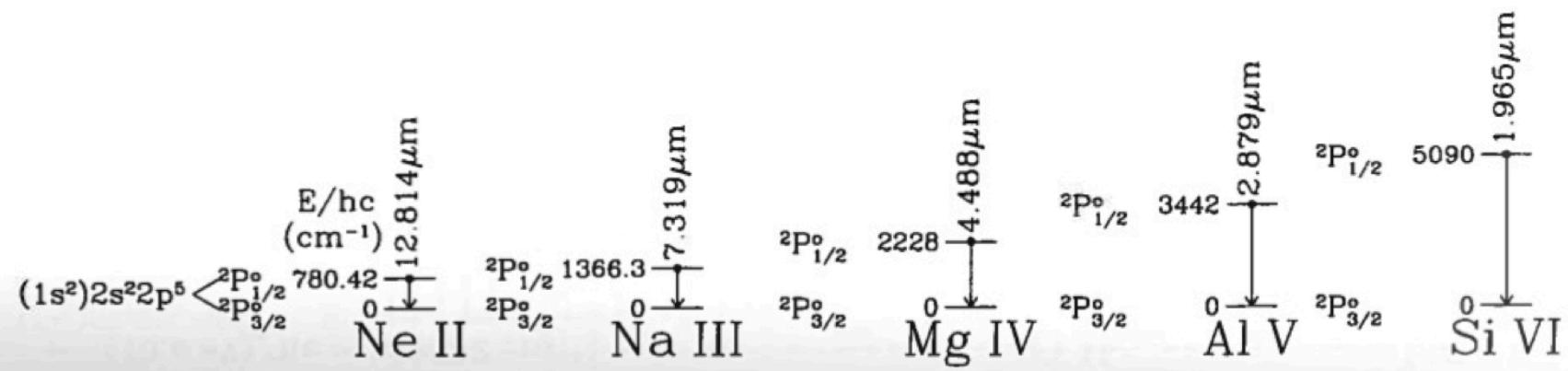
$$--- (13.6 \text{ eV})/\hbar c = 109692 \text{ cm}^{-1} ---$$



Fluorine-like ions

$$--- (13.6 \text{ eV})/\hbar c = 109692 \text{ cm}^{-1} ---$$

9 electrons



Ionization Potentials (eV)

Element	I→II	II→III	III→IV	IV→V	V→VI	VI→VII	VII→VIII
1 H	13.5984						
2 He	24.5874	54.416					
3 Li	5.3917	75.640	122.454				
4 Be	9.3227	18.211	153.894	217.719			
5 B	8.2980	25.155	37.931	259.375	340.226		
6 C	11.2603	24.383	47.888	64.494	392.089	489.993	
7 N	14.5341	29.601	47.449	77.474	97.890	552.072	667.046
8 O	13.6181	35.121	54.936	77.414	113.899	138.120	739.293
9 F	17.4228	34.971	62.708	87.140	114.243	147.163	185.189
10 Ne	21.5645	40.963	63.423	97.117	126.247	154.214	207.271
11 Na	5.1391	47.286	71.620	98.91	138.40	172.183	208.50
12 Mg	7.6462	15.035	80.144	109.265	141.270	186.76	225.02
13 Al	5.9858	18.829	28.448	119.992	153.825	190.477	241.76
14 Si	8.1517	16.346	33.493	45.142	166.767	205.267	246.481
15 P	10.4867	19.769	30.203	51.444	65.025	220.422	263.57
16 S	10.3600	23.338	34.790	47.222	72.594	88.053	280.948
17 Cl	12.9676	23.814	39.911	53.465	67.819	97.030	114.201
18 Ar	15.7596	27.630	40.735	59.686	75.134	91.00	124.328
19 K	4.3407	31.628	45.806	60.913	82.66	99.4	117.6
20 Ca	6.1132	11.872	50.913	67.27	84.51	108.8	127.2
21 Sc	6.5615	12.800	24.757	73.489	91.69	110.7	138.0
22 Ti	6.8281	13.576	24.492	43.267	123.7	119.533	140.846
23 V	6.7462	14.655	29.311	46.709	65.282	128.125	150.641
24 Cr	6.7665	16.486	30.959	49.160	69.456	90.635	160.175
25 Mn	7.4340	15.640	33.668	51.2	72.4	95.60	119.203
26 Fe	7.9024	16.188	30.651	54.801	75.010	99.063	124.976
27 Co	7.8810	17.084	33.50	51.27	79.5	102.	129.
28 Ni	7.6398	18.169	35.187	54.925	76.06	107.87	133.
29 Cu	7.7264	20.292	36.841	57.380	79.846	103.031	138.862
30 Zn	9.3492	17.964	39.723	59.573	82.574	133.903	133.903

Notes:

- Ionization potentials from Ralchenko et al. (2010)
- The light line separates ions with $I < I_{\text{He}} = 24.6 \text{ eV}$ from ions with $I > I_{\text{He}} = 24.6 \text{ eV}$.
- Ions to right of the heavy line (with $I > I_{\text{He II}} = 54.4 \text{ eV}$) are not abundant in gas photoionized by O or B stars and are therefore indicative of photo-ionization by WR stars, PN nuclei, or collisional ionization in shocked gas.
- For elemental abundances, see Table 1.4.