Appendix 1
Atomic Orbitals

THE spacial distribution of electron density in an atom is described by means of atomic orbitals $\psi(r, \theta, \phi)$ such that for a given orbital ψ the function $\psi^2 dv$ gives the probability of finding the electron in an element of volume dv at a point having the polar coordinates r, θ, ϕ. Each orbital can be expressed as a product of two functions, i.e. $\psi_{n,l,m}(r, \theta, \phi) = R_{n,l}(r)A_{l,m}(\theta, \phi)$, where

(a) $R_{n,l}(r)$ is a radial function which depends only on the distance r from the nucleus (independent of direction) and is defined by the two quantum numbers n, l;

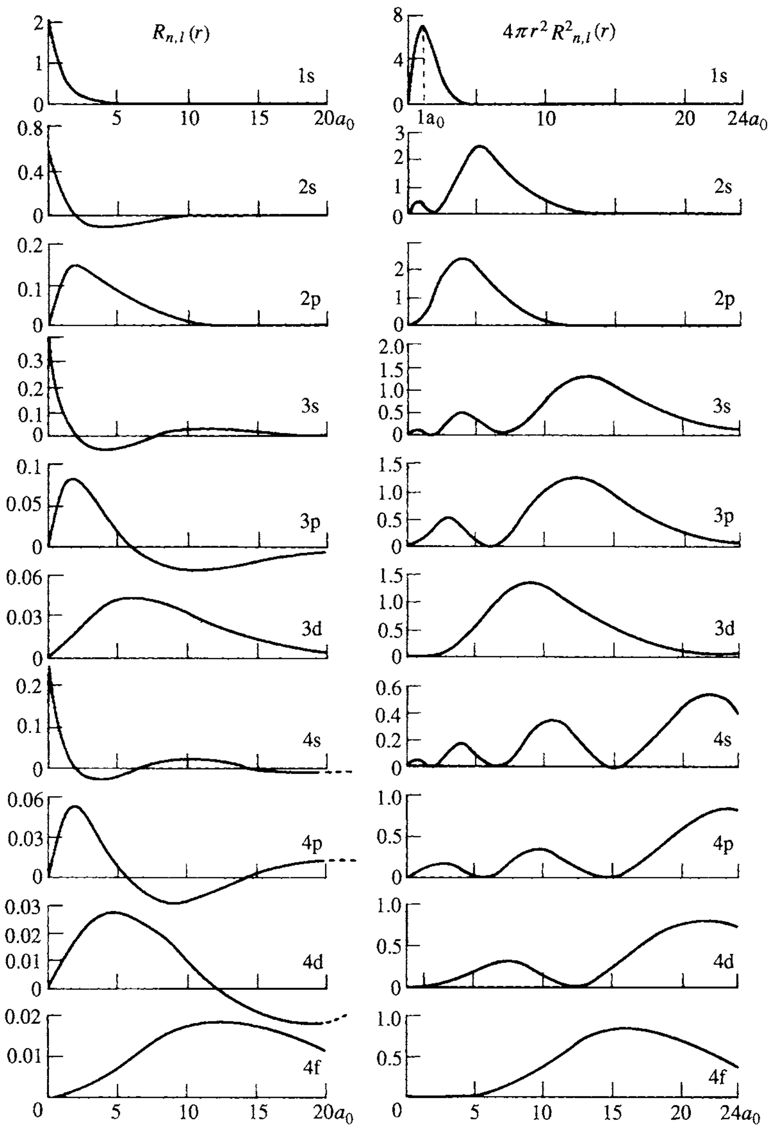
(b) $A_{l,m}(\theta, \phi)$ is an angular function which is independent of distance but depends on the direction as given by the angles θ, ϕ; it is defined by the two quantum numbers l, m.

Normalized radial functions for a hydrogen-like atom are given in Table A1.1 and plotted graphically in Fig. A1.1 for the first ten combinations of n and l. It will be seen that the radial functions for 1s, 2p, 3d, and 4f orbitals have no nodes and are everywhere of the same sign (e.g. positive). In general $R_{n,l}(r)$ becomes zero $(n - l - 1)$ times between r equals 0 and ∞. The probability of finding an electron at a distance r from the nucleus is given by $4\pi R^2_{n,l}(r)r^2 dr$, and this is also plotted in Fig. A1.1. However, the probability of finding an electron frequently depends also on the direction chosen. The probability of finding an electron in a given direction, independently of distance from the nucleus, is given by the square of the angular dependence function $A^2_{l,m}(\theta, \phi)$. The normalized functions $A_{l,m}(\theta, \phi)$ are listed in Table A1.2 and illustrated schematically by the models in Fig. A1.2. It will be seen that for s orbitals ($l = 0$) the angular dependence function A is constant, independent of θ, and ϕ, i.e. the function is spherically symmetrical. For p orbitals ($l = 1$) A comprises two spheres in contact, one being positive and one negative, i.e. there is one planar node. The d and f functions ($l = 2, 3$) have more complex angular dependence with 2 and 3 nodes respectively.

Table A1.1 Normalized radial functions $R_{n,l}(r)$ for hydrogen-like atoms

$$R_{n,l}(r) = -\sqrt{\frac{4(n-l-1)!Z^3}{n^4[(n+l)!]^3 a_0^3}} \times \left(\frac{2Zr}{a_0 n}\right)^l L_{n+1}^{2l+1}\left(\frac{2Zr}{a_0 n}\right) \times e^{-Zr/a_0 n}$$

Orbital	n	l	$R_{n,l}$	= Constant	× Polynomial	× Expon.
1s	1	0	$R_{1,0}$	$2(Z/a_0)^{3/2}$	1	e^{-Zr/a_0}
2s	2	0	$R_{2,0}$	$\dfrac{(Z/a_0)^{3/2}}{2\sqrt{2}}$	$\left(2-\dfrac{Zr}{a_0}\right)$	$e^{-Zr/2a_0}$
2p	2	1	$R_{2,1}$	$\dfrac{(Z/a_0)^{3/2}}{2\sqrt{6}}$	$\dfrac{Zr}{a_0}$	$e^{-Zr/2a_0}$
3s	3	0	$R_{3,0}$	$\dfrac{2(Z/a_0)^{3/2}}{81\sqrt{3}}$	$\left(27-18\dfrac{Zr}{a_0}+2\dfrac{Z^2r^2}{a_0^2}\right)$	$e^{-Zr/3a_0}$
3p	3	1	$R_{3,1}$	$\dfrac{4(Z/a_0)^{3/2}}{81\sqrt{6}}$	$\left(6\dfrac{Zr}{a_0}-\dfrac{Z^2r^2}{a_0^2}\right)$	$e^{-Zr/3a_0}$
3d	3	2	$R_{3,2}$	$\dfrac{4(Z/a_0)^{3/2}}{81\sqrt{30}}$	$\dfrac{Z^2r^2}{a_0^2}$	$e^{-Zr/3a_0}$
4s	4	0	$R_{4,0}$	$\dfrac{(Z/a_0)^{3/2}}{768}$	$\left(192-144\dfrac{Zr}{a_0}+24\dfrac{Z^2r^2}{a_0^2}-\dfrac{Z^3r^3}{a_0^3}\right)$	$e^{-Zr/4a_0}$
4p	4	1	$R_{4,1}$	$\dfrac{(Z/a_0)^{3/2}}{265\sqrt{15}}$	$\left(80\dfrac{Zr}{a_0}-20\dfrac{Z^2r^2}{a_0^2}+\dfrac{Z^3r^3}{a_0^3}\right)$	$e^{-Zr/4a_0}$
4d	4	2	$R_{4,2}$	$\dfrac{(Z/a_0)^{3/2}}{768\sqrt{5}}$	$\left(12\dfrac{Z^2r^2}{a_0^2}-\dfrac{Z^3r^3}{a_0^3}\right)$	$e^{-Zr/4a_0}$
4f	4	3	$R_{4,3}$	$\dfrac{(Z/a_0)^{3/2}}{768\sqrt{35}}$	$\dfrac{Z^3r^3}{a_0^3}$	$e^{-Zr/4a_0}$



Radial functions for hydrogen atom.

Figure A1.1 Radial functions for a hydrogen atom. (Note that the horizontal scale is the same in each graph but the vertical scale varies by as much as a factor of 100. The Bohr radius $a_0 = 52.9\,\text{pm}$.)

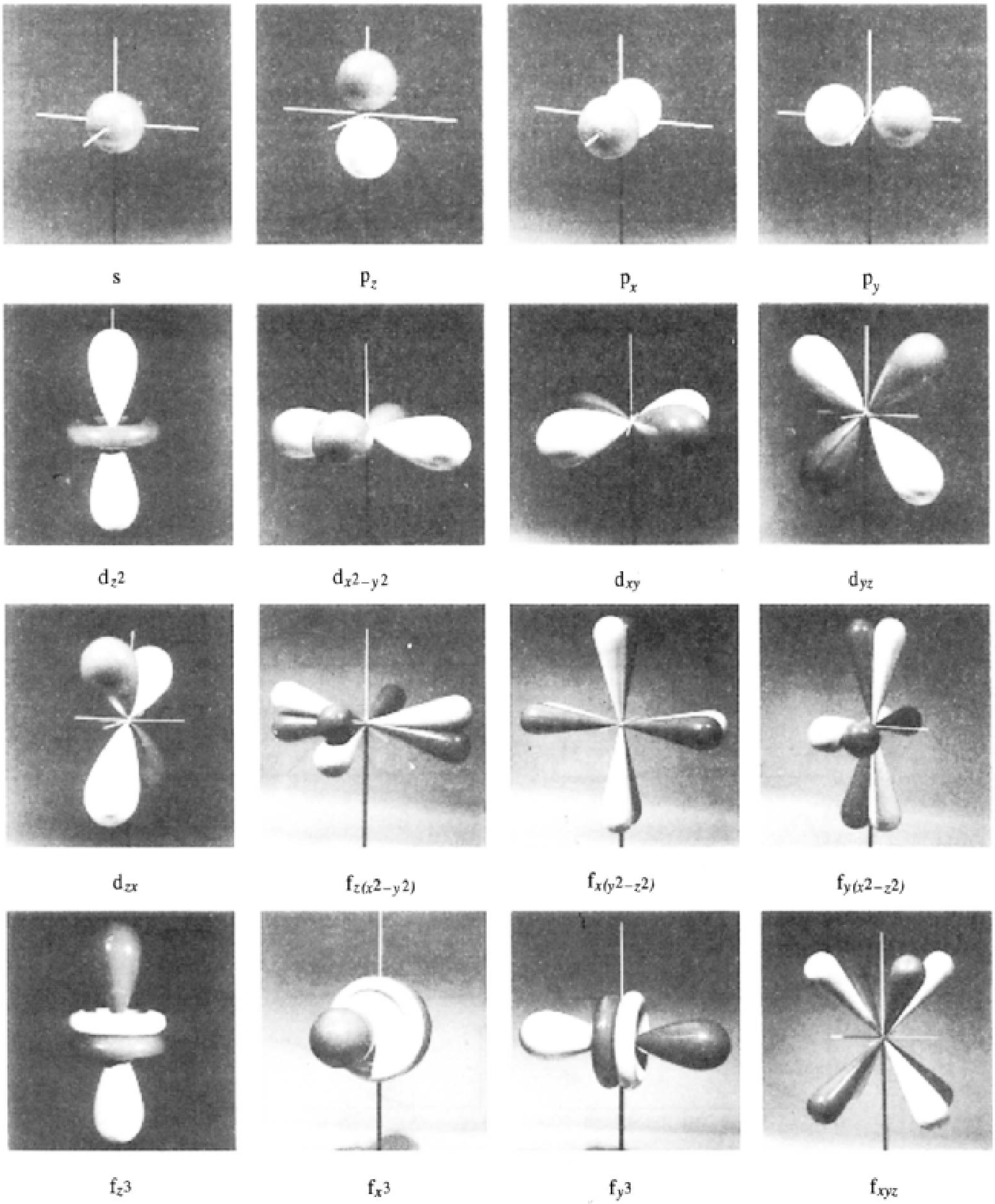


Figure A1.2 Models schematically illustrating the angular dependence functions $A_{l,m}(\theta, \phi)$. There is no unique way of representing the angular dependence functions of all seven f orbitals. An alternative to the set shown is one f_{z^3}, three f_{xz^2}, f_{yx^2}, f_{zy^2}, and three $f_{x(x^2-3y^2)}$, $f_{y(y^2-3z^2)}$, and $f_{z(z^2-3x^2)}$.

Table A1.2 Normalized angular dependence functions, $A_{l,m}(\theta,\ \phi) = \Theta_{l,m}(\theta)\Phi_m(\phi)$

Orbital	Angular dependence function	Orbital	Angular dependence function
s	$\frac{1}{2\sqrt{\pi}}$		
p_z	$\frac{\sqrt{3}}{2\sqrt{\pi}}\cos\theta$		
p_x	$\frac{\sqrt{3}}{2\pi}\sin\theta\cos\phi$	f_{z^3}	$\frac{\sqrt{7}}{4\sqrt{\pi}}(5\cos^3\theta - 3\cos\theta)$
p_y	$\frac{\sqrt{3}}{2\sqrt{\pi}}\sin\theta\sin\phi$	f_{z^2x}	$\frac{\sqrt{42}}{8\sqrt{\pi}}(5\cos^2\theta - 1)\sin\theta\cos\phi$
d_{z^2}	$\frac{\sqrt{5}}{4\sqrt{\pi}}(3\cos^2\theta - 1)$	f_{z^2y}	$\frac{\sqrt{42}}{8\sqrt{\pi}}(5\cos^2\theta - 1)\sin\theta\sin\phi$
$d_{x^2-y^2}$	$\frac{\sqrt{15}}{4\sqrt{\pi}}\sin^2\theta(2\cos^2\phi - 1)$	$f_{z(x^2-y^2)}$	$\frac{\sqrt{105}}{4\sqrt{\pi}}\cos\theta\sin^2\theta(2\cos^2\phi - 1)$
d_{zx}	$\frac{\sqrt{15}}{2\sqrt{\pi}}\cos\theta\sin\theta\cos\phi$	f_{zxy}	$\frac{\sqrt{105}}{2\sqrt{\pi}}\cos\theta\sin^2\theta\cos\phi\sin\phi$
d_{zy}	$\frac{\sqrt{15}}{2\sqrt{\pi}}\cos\theta\sin\theta\sin\phi$	f_{x^3}	$\frac{\sqrt{70}}{8\sqrt{\pi}}\sin^3\theta(4\cos^3\phi - 3\cos\phi)$
d_{xy}	$\frac{\sqrt{15}}{2\sqrt{\pi}}\sin^2\theta\sin\phi\cos\phi$	f_{y^3}	$\frac{\sqrt{70}}{8\sqrt{\pi}}\sin^3\theta(3\sin\phi - 4\sin^3\phi)$

Appendix 2
Symmetry Elements, Symmetry Operations and Point Groups

An object has *symmetry* when certain parts of it can be interchanged with others without altering either the identity or the apparent orientation of the object. For a discrete object such as a molecule 5 *elements of symmetry* can be envisaged:

> *axis* of symmetry, C;
> *plane* of symmetry, σ;
> *centre of inversion*, i;
> *improper axis* of symmetry, S; and
> *identity*, E.

These elements of symmetry are best recognized by performing various *symmetry operations*, which are geometrically defined ways of exchanging equivalent parts of a molecule. The 5 symmetry operations are:

- $\mathbf{C}_n$, *rotation* of the molecule about a symmetry *axis* through an angle of $360°/n$; n is called the *order* of the rotation (twofold, threefold, etc.);
- $\boldsymbol{\sigma}$ reflection of all atoms through a *plane* of the molecule;
- **i**, inversion of all atoms through a *point* of the molecule;
- $\mathbf{S}_n$, *Rotation* of the molecule through an angle $360°/n$ *followed by reflection* of all atoms through a plane perpendicular to the axis of rotation; the combined operation (which may equally follow the sequence *reflection then rotation*) is called *improper rotation*;
- **E**, the *identity* operation which leaves the molecule unchanged.

The rotation axis of highest order is called the *principal axis* of rotation; it is usually placed in the vertical direction and designated the z-axis of the molecule. Planes of reflection which are perpendicular to the principal axis are called *horizontal planes (h)*. Planes of reflection which contain the principal axis are called *vertical planes (v)*, or *dihedral planes (d)* if they bisect 2 twofold axes.

The complete set of symmetry operations that can be performed on a molecule is called the *symmetry group* or *point group* of the molecule and the *order* of the point group is the number of symmetry operations it contains. Table A2.1 lists the various point groups, together with their elements of symmetry and with examples of each.

Table A2.1 Point groups

Point group	Elements of symmetry	Examples
C_1	E	CHFClBr
C_s	E, σ	SO_2FBr, HOCl, BFClBr, $SOCl_2$, SF_5NF_2
C_i	E, i	CHClBr–CHClBr (staggered)
C_2	E, C_2	H_2O_2, *cis*-$[Co(en)_2X_2]$
C_3	E, C_3	PPh_3 (propeller)
C_{2v}	$E, C_2, 2\sigma_v$	H_2O (V-Shaped), H_2CO (Y-shaped), ClF_3 (T-shaped), SF_4 (see-saw), SiH_2Cl_2, *cis*-$[Pt(NH_3)_2Cl_2]$, C_6H_5Cl
C_{3v}	$E, C_3, 3\sigma_v$	GeH_3Cl, PCl_3, $O{=}PF_3$
C_{4v}	$E, C_4, 4\sigma_v$	SF_5Cl, IF_5, $XeOF_4$
C_{5v}	$E, C_5, 5\sigma_v$	$[Ni(\eta^5\text{-}C_5H_5)(NO)]$
C_{6v}	$E, C_6, 6\sigma_v$	$[Cr(\eta^6\text{-}C_6H_6)(\eta^6\text{-}C_6Me_6)]$
$C_{\infty v}$	$E, C_\infty, \infty\sigma_v$	NO, HCN, COS
C_{2h}	E, C_2, σ_h, i	*trans*-N_2F_4
C_{3h}	E, C_3, σ_h, i	$B(OH)_3$
C_{4h}	E, C_4, σ_h, i	$[Re_2(\mu,\eta^2\text{-}SO_4)_4]$
D_3	$E, C_3, 3C'_2$	trischelates $[M(chel)_3]$, C_2H_6 (*gauche*)
D_{2d}	$E, C_2, 2C'_2, 2\sigma_d, S_4$	B_2Cl_4 (vapour, staggered), As_4S_4
D_{3d}	$E, C_3, 3C'_2, 3\sigma_d, i, S_6$	$R_3W{\equiv}WR_3$ (staggered)
D_{4d}	$E, C_4, 4C'_2, 4\sigma_d, S_8$	S_8 (crown), *closo*-$B_{10}H_{10}{}^{2-}$
D_{2h}	$E, C_2, 2C'_2, 2\sigma_v, \sigma_h, i$	B_2Cl_4 (planar), B_2H_6, *trans*-$[Pt(NH_3)_2Cl_2]$, *trans*-$[Co(NH_3)_2Cl_2Br_2]^-$, 1,4-$C_6H_4Cl_2$
D_{3h}	$E, C_3, 3C'_2, 3\sigma_v, \sigma_h, S_3$	BCl_3, PF_5, $B_3N_3H_6$, $[ReH_9]^{2-}$
D_{4h}	$E, C_4, 4C'_2, 4\sigma_v, \sigma_h, i, S_4$	XeF_4, $PtCl_4{}^{2-}$, *trans*-$[Co(NH_3)_4Cl_2]^+$, $[Re_2Cl_8]^{2-}$, *closo*-1,6-$C_2B_4H_6$
D_{5h}	$E, C_5, 5C'_2, 5\sigma_v, \sigma_h, S_5$	$[Fe(\eta^5\text{-}C_5H_5)_2]$ eclipsed, $B_7H_7{}^{2-}$, IF_7
D_{6h}	$E, C_6, 6C'_2, 6\sigma_v, \sigma_h, i, S_6$	C_6H_6, $[Cr(\eta^6\text{-}C_6H_6)_2]$ (eclipsed)
$D_{\infty h}$	$E, C_\infty, \infty C'_2, \infty\sigma_v, i$	Cl_2, CO_2
S_4	E, S_4	*cyclo*-$Cl_4B_4N_4R_4$
T	$E, 3C_2, 4C_3$	$Si(SiMe_3)_4$, $[Pt(PF_3)_4]$
T_d	$E, 4C_3, 6\sigma_d, 3S_4$	SiF_4, B_4Cl_4, $[Ni(CO)_4]$, $[Ir_4(CO)_{12}]$
T_h	$E, 4C_3, 3C_2, 3\sigma_h, i, 4S_6$	$[Co(NO_2)_6]^{3-}$ (*trans* NO_2 groups eclipsed), $[M(\eta^2\text{-}NO_3)_6]^{n-}$, $[W(NMe_2)_6]$
O_h	$E, 3C_4, 4C_3, 6C'_2, 3\sigma_h, 6\sigma_d, i, 3S_4, 4S_6$	SF_6, $B_6H_6{}^{2-}$ (octahedron), C_8H_8 (cubane)
I_h	$E, 6C_5, 10C_3, 15C_2, 15\sigma_v, i, 12S_{10}, 10S_6$	$B_{12}H_{12}{}^{2-}$ (icosahedron)

It is instructive to add to these examples from the numerous instances of point group symmetry mentioned throughout the text. In this way a facility will gradually be acquired in discerning the various elements of symmetry present in a molecule.

A convenient scheme for identifying the point group symmetry of any given species is set out in the flow chart.(1) Starting at the top of the chart each vertical line asks a question: if the answer is "yes" then move to the right, if "no" then move to the left until the correct point group is arrived at. Other similar schemes have been devised.(2–5)

[1] J. Donohue, *Sov. Phys. Crystallogr.* **26**, 516 (1981); *Kristallografiya* **26**, 908–9 (1981).

[2] R. L. Carter, *J. Chem. Educ.* **45**, 44 (1968).

[3] F. A. Cotton, *Chemical Applications of Group Theory*, 2nd edn., pp. 45–7, Wiley-Interscience, New York, 1971.

[4] J. D. Donaldson and S. D. Ross, *Symmetry and Stereochemistry*, pp. 35–49, Intertext Books, London, 1972.

[5] J. A. Salthouse and M. J. Ware, *Point Group Character Tables and Related Data*, p. 29, Cambridge University Press, 1972.

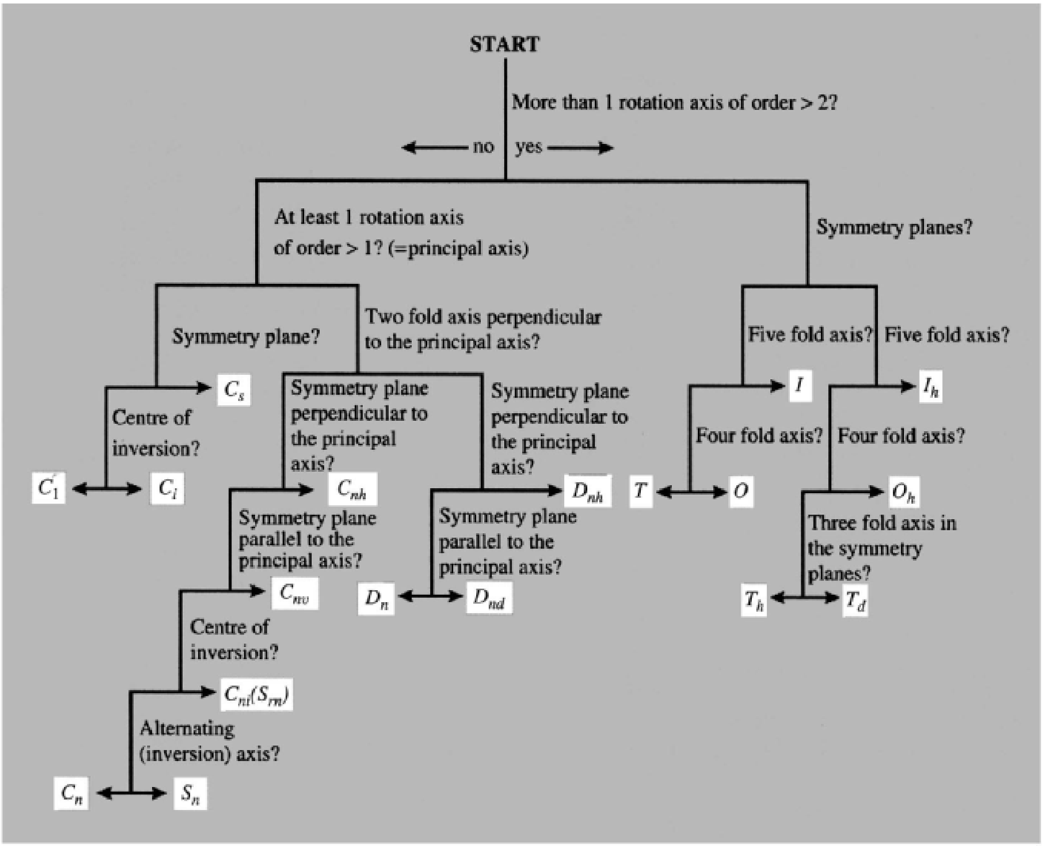


Figure A2.1 Point group symmetry flow chart.

Appendix 3
Some Non-SI Units†

Physical quantity	Name of unit	Symbol for unit	Definition of unit
Length	ångström	Å	10^{-10} m (100 pm)
Time	minute	min	60 s
	hour	h	3600 s
	day	d	86 400 s
Energy	erg	erg	10^{-7} J
	kilowatt hour	kWh	3.6×10^{6} J
	thermochemical calorie	cal_{th}	4.184 J
Force	dyne	dyn	10^{-5} N
Pressure	bar	bar	10^{5} Pa
	atmosphere	atm	101 325 Pa
	conventional millimetre of mercury	mmHg	$13.5951 \times 9.806\,65$ Pa i.e. 133.322 Pa
	torr	Torr	(101 325/760) Pa
Magnetic flux	maxwell	Mx	10^{-8} Wb
Magnetic flux density (magnetic induction)	gauss	G, Gs	10^{-4} T
Dynamic viscosity	poise	P	10^{-1} Pa s
Concentration	–	M	mol dm^{-3}
Radioactivity	curie	Ci	3.7×10^{10} s^{-1}
Radioactive exposure	röntgen	R	2.58×10^{-4} C kg^{-1}
Absorbed dose	rad	rad	10^{-2} J kg^{-1}
Angle	degree	°	$1° = (\pi/180)$ radian

†The unit "degree Celsius" (°C) is identical with the kelvin (K). The Celsius temperature (t_C) is related to the thermodynamic temperature T by the definition: $t_C = T - 273.15$ K.

Some useful conversion factors:

1 m = 3.280 839 9 ft = 39.370 079 inches
1 inch = 25.4 mm (defined)
1 statute mile = 1.609 344 km
1 light year = $9.460\,55 \times 10^{12}$ km
1 acre = 4046.8564 m^2
1 gal (Imperial) = 1.200 949 gal (US) = 4.545 960 1
1 gal (US) = 0.832 674 7 gal (Imp.) = 3.785 411 8 1
1 lb (avoirdupois) = 0.453 592 37 kg
1 oz (avoirdupois) = 28.349 527 g
1 oz (troy, or apoth.) = 31.103 486 g
1 carat = 3.086 47 grains = 200 mg
1 tonne = 1000 kg = 2204.622 6 lb = 1.102 311 3 short tons
1 short ton = 907.184 74 kg = 2000 lb = 0.892 857 14 long tons
1 long ton = 1016.046 9 kg = 2240 lb = 1.120 short tons
1 atm = 101 325 Pa = 1.013 25 bar = 760 Torr = 14.695 95 lb/in^2
1 Pa = 10^{-5} bar ~ $1.019\,716 \times 10^{-1}$ kg m^{-2} = $0.986\,923 \times 10^{-5}$ atm
1 mdyn $Å^{-1}$ = 100 N m^{-1}
1 calorie (thermochem) = 4.184 J (defined)
1 eV = $1.602\,19 \times 10^{-19}$ J
1 eV/molecule = 96.484 56 kJ mol^{-1} = 23.060 36 kcal mol^{-1}

Appendix 4
Abundance of Elements in Crustal Rocks/ppm (i.e. g/tonne)[†]

No.	Elt.	ppm	Σ%	No.	Elt.	ppm	No.	Elt.	ppm	No.	Elt.	ppm
1	O	455 000	*45.50*	20	Cl	126	39	Th	8.1	58	Tl	0.7
2	Si	272 000	*72.70*	21	Cr	122	40	Sm	7.0	59	Tm	0.5
3	Al	83 000	*81.00*	22	Ni	99	41	Gd	6.1	60	I	0.46
4	Fe	62 000	*87.20*	23	Rb	78	42	Er	3.5	61	In	0.24
5	Ca	46 600	*91.86*	24	Zn	76	43	Yb	3.1	62	Sb	0.2
6	Mg	27 640	*94.62*	25	Cu	68	44	Hf	2.8	63	Cd	0.16
7	Na	22 700	*96.89*	26	Ce	66	45	Cs	2.6	64	Ag	0.08
8	K	18 400	*98.73*	27	Nd	40	46	Br	2.5		Hg	0.08
9	Ti	6320	*99.36*	28	La	35	47	U	2.3	66	Se	0.05
10	H	1520	*99.51*	29	Y	31	48	Sn	2.1	67	Pd	0.015
11	P	1120	*99.63*	30	Co	29		Eu	2.1	68	Pt	0.01
12	Mn	1060	*99.73*	31	Sc	25	50	Be	2	69	Bi	0.008
13	F	544	*99.79*	32	Nb	20	51	As	1.8	70	Os	0.005
14	Ba	390	*99.83*	33	N	19	52	Ta	1.7	71	Au	0.004
15	Sr	384	*99.86*		Ga	19	53	Ge	1.5	72	Ir	0.001
16	S	340	*99.90*	35	Li	18	54	Ho	1.3		Te	0.001
17	C	180	*99.92*	36	Pb	13		Mo	1.2	74	Re	0.0007
18	Zr	162	*99.93*	37	Pr	9.1	55	W	1.2	75	Ru	0.0001
19	V	136	*99.95*	38	B	9		Tb	1.2		Rh	0.0001

[†]Taken from W. S. Fyfe, *Geochemistry*, Oxford University Press, 1974, with some modifications and additions to incorporate later data. The detailed numbers are subject to various assumptions in the models of the global distribution of the various rock types within the crust, but they are broadly acceptable as an indication of elemental abundances. See also Table 1 in C. K. Jørgensen, *Comments Astrophys.* **17**, 49–101 (1993).

Appendix 5
Effective Ionic Radii in pm for Various Oxidation States† (in parentheses)

s Block

Li (+1) 76	**Be** (+2) 45
Na (+1) 102	**Mg** (+2) 72.0
K (+1) 138	**Ca** (+2) 100
Rb (+1) 152	**Sr** (+2) 118
Cs (+1) 167	**Ba** (+2) 135
Fr (+1) 180	**Ra** $(+2)^{\mathrm{VIII}}$ 148

p Block

B (+3) 27	**C** (+4) 16	**N** $(-3)^{\mathrm{IV}}$ 146 (+3) 16 (+5) 13	**O** (−2) 140	**F** (−1) 133 (+7) 8	
Al (+3) 53.5	**Si** (+4) 40	**P** (+3) 44 (+5) 38	**S** (−2) 184 (+4) 37 (+6) 29	**Cl** (−1) 184 $(+5)^{\mathrm{III}}$ 12 (+7) 27	
Ga (+3) 62.0	**Ge** (+2) 73 (+4) 53.0	**As** (+3) 58 (+5) 46	**Se** (−2) 198 (+4) 50 (+6) 42	**Br** (−1) 196 $(+3)^{\mathrm{IV}}_{\mathrm{Sq}}$ 59 $(+5)^{\mathrm{III}}$ 31 (+7) 39	
In (+3) 80.0	**Sn** (+2) 118 (+4) 69.0	**Sb** (+3) 76 (+5) 60	**Te** (−2) 221 (+4) 97 (+6) 56	**I** (−1) 220 (+5) 95 (+7) 53	**Xe** (+8) 48
Tl (+1) 150 (+3) 88.5	**Pb** (+2) 119 (+4) 77.5	**Bi** (+3) 103 (+5) 76	**Po** (+4) 94 (+6) 67	**At** (+7) 62	

d Block

	Sc	**Ti**	**V**	**Cr**	**Mn**	**Fe**	**Co**	**Ni**	**Cu**	**Zn**	
(+1)									77		(+1)
(+2)		86	79	73 ls 80 hs	67	61 ls 78.0 hs	65 ls 74.5 hs	69	73	74.0	(+2)
(+3)	74.5	67.0	64.0	61.5	58 ls 64.5 hs	55 ls 64.5 hs	54.5 ls 61 hs	56 ls 60 hs	54 ls		(+3)
(+4)		60.5	58	55	53.0	58.5	53	48 ls			(+4)
(+5)			54	49	33^{IV}	–					(+5)
(+6)				44	25.5^{IV}	25^{IV}					(+6)
(+7)					46						(+7)

	Y	**Zr**	**Nb**	**Mo**	**Tc**	**Ru**	**Rh**	**Pd**	**Ag**	**Cd**	
(+1)								59^{II}	115		(+1)
(+2)								86	94	95	(+2)
(+3)	90.0		72	69		68	66.5	76	75		(+3)
(+4)		72	68	65	64.5	62.0	60	61.5			(+4)
(+5)			64	61	60	56.5	55				(+5)
(+6)				59	–	–					(+6)
(+7)					56	38^{IV}					(+7)
(+8)						36^{IV}					(+8)

	La	**Hf**	**Ta**	**W**	**Re**	**Os**	**Ir**	**Pt**	**Au**	**Hg**	
(+1)									137	119	(+1)
(+2)								86	–	102	(+2)
(+3)	103.2		72				68	–	85		(+3)
(+4)		71	68	66	63	63.0	62.5	62.5	–		(+4)
(+5)			64	62	58	57.5	57	57	57		(+5)
(+6)				60	55	54.5					(+6)
(+7)					53	52.5					(+7)
(+8)						39^{IV}					(+8)

	Ac
+3	112

f Block

	Ce	**Pr**	**Nd**	**Pm**	**Sm**	**Eu**	**Gd**	**Tb**	**Dy**	**Ho**	**Er**	**Tm**	**Yb**	**Lu**	
(+2)			129^{VIII}		122^{VII}	117			107			103	102		(+2)
(+3)	102	99	98.3	97	95.8	94.7	93.8	92.3	91.2	90.1	89.0	88.0	86.8	86.1	(+3)
(+4)	87	85						76							(+4)

	Th	**Pa**	**U**	**Np**	**Pu**	**Am**	**Cm**	**Bk**	**Cf**	**Es**	**Fm**	**Md**	**No**	**Lr**	
(+2)				110		126^{VIII}									(+2)
(+3)		104	102.5	101	100	97.5	97	96	95						(+3)
(+4)	94	90	89	87	86	85	85	83	82.1						(+4)
(+5)		78	78	75	74										(+5)
(+6)			73	72	71										(+6)
(+7)				71											(+7)

†For coord. no. 6 unless indicated by superscript numerals$^{\mathrm{III}}$,$^{\mathrm{IV}}$, etc. (All data taken from R. D. Shannon, *Acta Cryst.* **A32**, 751–67 (1976).

Appendix 6
Nobel Prize for Chemistry

1901 **J. H. van't Hoff** (Berlin): discovery of the laws of chemical dynamics and osmotic pressure in solutions.

1902 **E. Fischer** (Berlin): sugar and purine syntheses.

1903 **S. Arrhenius** (Stockholm): electrolytic theory of dissociation.

1904 **W. Ramsay** (University College, London): discovery of the inert gaseous elements in air and their place in the periodic system.

1905 **A. von Baeyer** (Munich): advancement of organic chemistry and the chemical industry through work on organic dyes and hydroaromatic compounds.

1906 **H. Moissan** (Paris): isolation of the element fluorine and development of the electric furnace.

1907 **E. Buchner** (Berlin): biochemical researches and the discovery of cell-free fermentation.

1908 **E. Rutherford** (Manchester): investigations into the disintegration of the elements and the chemistry of radioactive substances.

1909 **W. Ostwald** (Gross-Bothen): work on catalysis and investigations into the fundamental principles governing chemical equilibria and rates of reaction.

1910 **O. Wallach** (Göttingen): pioneer work in the field of alicyclic compounds.

1911 **Marie Curie** (Paris): discovery of the elements radium and polonium, the isolation of radium, and the study of the nature and compounds of this remarkable element.

1912 **V. Grignard** (Nancy): discovery of the Grignard reagent.

P. Sabatier (Toulouse): method of hydrogenating organic compounds in the presence of finely disintegrated metals.

1913 **A. Werner** (Zürich): work on the linkage of atoms in molecules which has thrown new light on earlier investigations and opened up new fields of research especially in inorganic chemistry.

1914 **T. W. Richards** (Harvard): accurate determination of the atomic weight of a large number of chemical elements.

1915 **R. Willstätter** (Munich): plant pigments, especially chlorophyll.

1916 Not awarded

1917 Not awarded

1918 **F. Haber** (Berlin–Dahlem): the synthesis of ammonia from its elements.

1919 Not awarded
1920 **W. Nernst** (Berlin): work in thermochemistry.
1921 **F. Soddy** (Oxford): contributions to knowledge of the chemistry of radioactive substances and investigations into the origin and nature of isotopes.
1922 **F. W. Aston** (Cambridge): discovery, by means of the mass spectrograph, of isotopes in a large number of non-radioactive elements and for enunciation of the whole-number rule.
1923 **F. Pregl** (Graz): invention of the method of microanalysis of organic substances.
1924 Not awarded
1925 **R. Zsigmondy** (Göttingen): demonstration of the heterogeneous nature of colloid solutions by methods which have since become fundamental in modern colloid chemistry.
1926 **T. Svedberg** (Uppsala): work on disperse systems.
1927 **H. Wieland** (Munich): constitution of the bile acids and related substances.
1928 **A. Windaus** (Göttingen): constitution of the sterols and their connection with the vitamins.
1929 **A. Harden** (London) and **H. von Euler-Chelpin** (Stockholm): investigations on the fermentation of sugars and fermentative enzymes.
1930 **H. Fischer** (Munich): the constitution of haemin and chlorophyll and especially for the synthesis of haemin.
1931 **C. Bosch** and **F. Bergius** (Heidelberg): the invention and development of chemical high pressure methods.
1932 **I. Langmuir** (Schenectady, New York): discoveries and investigations in surface chemistry.
1933 Not awarded
1934 **H. C. Urey** (Columbia, New York): discovery of heavy hydrogen.
1935 **F. Joliot** and **Iréne Joliot-Curie** (Paris): synthesis of new radioactive elements.
1936 **P. Debye** (Berlin–Dahlem): contributions to knowledge of molecular structure through investigations on dipole moments and on the diffraction of X-rays and electrons in gases.
1937 **W. N. Haworth** (Birmingham): investigations on carbohydrates and vitamin C.
P. Karrer (Zürich): investigations of carotenoids, flavins, and vitamins A and B_2.
1938 **R. Kuhn** (Heidelberg): work on carotenoids and vitamins.
1939 **A. F. J. Butenandt** (Berlin): work on sex hormones.
L. Ruzicka (Zürich): work on polymethylenes and higher terpenes.
1940 Not awarded.
1941 Not awarded.
1942 Not awarded.
1943 **G. Hevesy** (Stockholm): use of isotopes as tracers in the study of chemical processes.
1944 **O. Hahn** (Berlin–Dahlem): discovery of the fission of heavy nuclei.
1945 **A. J. Virtanen** (Helsingfors): research and inventions in agricultural and nutrition chemistry, especially fodder preservation.
1946 **J. B. Sumner** (Cornell): discovery that enzymes can be crystallized.
J. H. Northrop and **W. M. Stanley** (Princeton): preparation of enzymes and virus proteins in a pure form.
1947 **R. Robinson** (Oxford): investigations on plant products of biological importance, especially the alkaloids.
1948 **A. W. K. Tiselius** (Uppsala): electrophoresis and adsorption analysis, especially for discoveries concerning the complex nature of the serum proteins.
1949 **W. F. Giauque** (Berkeley): contributions in the field of chemical thermodynamics, particularly concerning the behaviour of substances at extremely low temperatures.
1950 **O. Diels** (Kiel) and **K. Alder** (Cologne): discovery and development of the diene synthesis.
1951 **E. M. McMillan** and **G. T. Seaborg** (Berkeley): discoveries in the chemistry of the transuranium elements.

1952 **A. J. P. Martin** (London) and **R. L. M. Synge** (Bucksburn): invention of partition chromatography.
1953 **H. Staudinger** (Freiburg): discoveries in the field of macromolecular chemistry.
1954 **L. Pauling** (California Institute of Technology, Pasadena): research into the nature of the chemical bond and its application to the elucidation of the structure of complex substances.
1955 **V. du Vigneaud** (New York): biochemically important sulfur compounds, especially the first synthesis of a polypeptide hormone.
1956 **C. N. Hinshelwood** (Oxford) and **N. N. Semenov** (Moscow): the mechanism of chemical reactions.
1957 **A. Todd** (Cambridge): nucleotides and nucleotide co-enzymes.
1958 **F. Sanger** (Cambridge): the structure of proteins, especially that of insulin.
1959 **J. Heyrovský** (Prague): discovery and development of the polarographic method of analysis.
1960 **W. F. Libby** (Los Angeles): use of carbon-14 for age determination in archeology, geology, geophysics, and other branches of science.
1961 **M. Calvin** (Berkeley): research on the carbon dioxide assimilation in plants.
1962 **J. C. Kendrew** and **M. F. Perutz** (Cambridge): the structures of globular proteins.
1963 **K. Ziegler** (Mülheim/Ruhr) and **G. Natta** (Milan): the chemistry and technology of high polymers.
1964 **Dorothy Crowfoot Hodgkin** (Oxford): determinations by X-ray techniques of the structures of important biochemical substances.
1965 **R. B. Woodward** (Harvard): outstanding achievements in the art of organic synthesis.
1966 **R. S. Mulliken** (Chicago): fundamental work concerning chemical bonds and the electronic structure of molecules by the molecular orbital method.
1967 **M. Eigen** (Göttingen), **R. G. W. Norrish** (Cambridge) and **G. Porter** (London): studies of extremely fast chemical reactions, effected by disturbing the equilibrium by means of very short pulses of energy.
1968 **L. Onsager** (Yale): discovery of the reciprocity relations bearing his name, which are fundamental for the thermodynamics of irreversible processes.
1969 **D. H. R. Barton** (Imperial College, London) and **O. Hassel** (Oslo): development of the concept of conformation and its application in chemistry.
1970 **L. F. Leloir** (Buenos Aires): discovery of sugar nucleotides and their role in the biosynthesis of carbohydrates.
1971 **G. Herzberg** (Ottawa): contributions to the knowledge of electronic structure and geometry of molecules, particularly free radicals.
1972 **C. B. Anfinsen** (Bethesda): work on ribonuclease, especially concerning the connection between the amino-acid sequence and the biologically active conformation.
S. Moore and **W. H. Stein** (Rockefeller, New York): contributions to the understanding of the connection between chemical structure and catalytic activity of the active centre of the ribonuclease molecule.
1973 **E. O. Fischer** (Munich) and **G. Wilkinson** (Imperial College, London): pioneering work, performed independently, on the chemistry of the organometallic so-called sandwich compounds.
1974 **P. J. Flory** (Stanford): fundamental achievements both theoretical and experimental in the physical chemistry of macromolecules.
1975 **J. W. Cornforth** (Sussex): stereochemistry of enzyme-catalysed reactions.
V. Prelog (Zürich): the stereochemistry of organic molecules and reactions.
1976 **W. N. Lipscomb** (Harvard): studies on the structure of boranes illuminating problems of chemical bonding.

1977 **I. Prigogine** (Brussels): non-equilibrium thermodynamics, particularly the theory of dissipative structures.

1978 **P. Mitchell** (Bodmin, Cornwall): contributions to the understanding of biological energy transfer through the formulation of the chemiosmotic theory.

1979 **H. C. Brown** (Purdue) and **G. Wittig** (Heidelberg): for their development of boron and phosphorus compounds, respectively, into important reagents in organic synthesis.

1980 **P. Berg** (Stanford): the biochemistry of nucleic acids, with particular regard to recombinant-DNA.
W. Gilbert (Harvard) and **F. Sanger** (Cambridge): the determination of base sequences in nucleic acids.

1981 **K. Fukui** (Kyoto) and **R. Hoffmann** (Cornell): quantum mechanical studies of chemical reactivity.

1982 **A. Klug** (Cambridge): development of crystallographic electron microscopy and the structural elucidation of biologically important nucleic acid-protein complexes.

1983 **H. Taube** (Stanford): mechanisms of electron transfer reactions of metal complexes.

1984 **R. B. Merrifield** (Rockefeller, New York): development of methodology for the synthesis of peptides on a solid matrix.

1985 **H. A. Hauptman** (Buffalo, NY) and **J. Karle** (Washington, DC): outstanding achievements in the development of direct methods for the determination of crystal structures.

1986 **D. R. Herschbach** (Harvard), **Y. T. Lee** (Berkeley) and **J. C. Polanyi** (Toronto): contributions concerning the dynamics of chemical elementary processes.

1987 **D. J. Cram** (Los Angeles), **J.-M. Lehn** (Strasbourg) and **C. J. Pedersen** (Wilmington, Delaware): development and use of molecules with structure specific interactions of high selectivity.

1988 **J. Deisenhofer** (Dallas, Texas), **R. Huber** (Martinsried) and **H. Michel** (Frankfurt am Main): determination of the three-dimensional structure of a photosynthetic reaction centre.

1989 **S. Altman** (Yale) and **T. Cech** (Boulder, Colorado): discovery of the catalytic properties of RNA.

1990 **E. J. Corey** (Harvard): development of the theory and methodology of organic synthesis.

1991 **R. R. Ernst** (Eidgenössische Technische Hochschule, Zürich): contributions to the development of the methodology of high resolution nmr spectroscopy.

1992 **R. A. Marcus** (California Institute of Technology): contributions to the theory of electron transfer reactions in chemical systems.

1993 **K. B. Mullis** (La Jolla, California): invention of the polymerase chain reaction.
M. Smith (University of British Columbia): fundamental contributions to the establishment of oligonucleotide-based, site-directed mutagenesis and its development for protein studies.

1994 **G. A. Olah** (University of Southern California): contributions to carbocation chemistry.

1995 **P. Crutzen** (Max Planck Institute for Chemistry, Mainz), **M. Molina** (Massachusetts Institute of Technology) and **F. S. Rowland** (Irvine, California): work in atmospheric chemistry, particularly concerning the formation and decomposition of ozone.

1996 **R. F. Curl** (Rice University, Texas), **H. Kroto** (Sussex University) and **R. E. Smalley** (Rice University, Texas): discovery of a new form of carbon, the fullerenes.

1997 **P. D. Boyer** (Los Angeles) and
J. E. Walker (Cambridge): pioneering work on enzymes that participate in the conversion of ATP.
J. C. Scou (Aarhus): discovery of the first molecular pump, an ion-transporting enzyme Na^+-K^+ ATPase.

Appendix 7
Nobel Prize for Physics

1901 **W. C. Röntgen** (Munich): discovery of the remarkable rays subsequently named after him.

1902 **H. A. Lorentz** (Leiden) and **P. Zeeman** (Amsterdam): influence of magnetism upon radiation phenomena.

1903 **H. A. Becquerel** (École Polytechnique, Paris): discovery of spontaneous radioactivity.

P. Curie and **Marie Curie** (Paris): researches on the radiation phenomena discovered by H. Becquerel.

1904 **Lord Rayleigh** (Royal Institution, London): investigations of the densities of the most important gases and for the discovery of argon in connection with these studies.

1905 **P. Lenard** (Kiel): work on cathode rays.

1906 **J. J. Thomson** (Cambridge): theoretical and experimental investigations on the conduction of electricity by gases.

1907 **A. A. Michelson** (Chicago): optical precision instruments and the spectroscopic and metrological investigations carried out with their aid.

1908 **G. Lippmann** (Paris): method of reproducing colours photographically based on the phenomenon of interference.

1909 **G. Marconi** (London) and **F. Braun** (Strasbourg): the development of wireless telegraphy.

1910 **J. D. van der Waals** (Amsterdam): the equation of state for gases and liquids.

1911 **W. Wien** (Würzburg): the laws governing the radiation of heat.

1912 **G. Dalén** (Stockholm): invention of automatic regulators for use in conjunction with gas accumulators for illuminating lighthouses and buoys.

1913 **H. Kamerlingh Onnes** (Leiden): properties of matter at low temperatures and production of liquid helium.

1914 **M. von Laue** (Frankfurt): discovery of the diffraction of X-rays by crystals.

1915 **W. H. Bragg** (University College, London) and **W. L. Bragg** (Manchester): analysis of crystal structure by means of X-rays.

1916 Not awarded.

1917 **C. G. Barkla** (Edinburgh): discovery of the characteristic Röntgen radiation of the elements.

1918 **M. Planck** (Berlin): services rendered to the advancement of physics by discovery of energy quanta.

1919 **J. Stark** (Greifswald): discovery of the Doppler effect on canal rays and of the splitting of spectral lines in electric fields.

1920 **C. E. Guillaume** (Sévres): service rendered to precise measurements in physics by discovery of anomalies in nickel steel alloys.

1921 **A. Einstein** (Berlin): services to theoretical physics, especially discovery of the law of the photoelectric effect.

1922 **N. Bohr** (Copenhagen): investigations of the structure of atoms, and of the radiation emanating from them.

1923 **R. A. Millikan** (California Institute of Technology, Pasadena): work on the elementary charge of electricity and on the photo-electric effect.

1924 **M. Siegbahn** (Uppsala): discoveries and researches in the field of X-ray spectroscopy.

1925 **J. Franck** (Göttingen) and **G. Hertz** (Halle): discovery of the laws governing the impact of an electron upon an atom.

1926 **J. Perrin** (Paris): the discontinuous structure of matter, and especially for the discovery of sedimentation equilibrium.

1927 **A. H. Compton** (Chicago): discovery of the effect named after him.
C. T. R. Wilson (Cambridge): method of making the paths of electrically charged particles visible by condensation of vapour.

1928 **O. W. Richardson** (King's College, London): thermionic phenomenon and especially discovery of the law named after him.

1929 **L. V. de Broglie** (Paris): discovery of the wave nature of electrons.

1930 **V. Raman** (Calcutta): work on the scattering of light and discovery of the effect named after him.

1931 Not awarded.

1932 **W. Heisenberg** (Leipzig): the creation of quantum mechanics, the application of which has, inter alia, led to the discovery of the allotropic forms of hydrogen.

1933 **E. Schrödinger** (Berlin) and **P. A. M. Dirac** (Cambridge): discovery of new productive forms of atomic theory.

1934 Not awarded.

1935 **J. Chadwick** (Liverpool): discovery of the neutron.

1936 **V. F. Hess** (Innsbruck): discovery of cosmic radiation.
C. D. Anderson (California Institute of Technology, Pasadena): discovery of the positron.

1937 **C. J. Davisson** (New York) and **G. P. Thomson** (London): experimental discovery of the diffraction of electrons by crystals.

1938 **E. Fermi** (Rome): demonstration of the existence of new radioactive elements produced by neutron irradiation and for the related discovery of nuclear reactions brought about by slow neutrons.

1939 **E. O. Lawrence** (Berkeley): invention and development of the cyclotron and for results obtained with it, especially with regard to artificial radioactive elements.

1940 Not awarded.

1941 Not awarded.

1942 Not awarded.

1943 **O. Stern** (Pittsburgh): development of the molecular ray method and discovery of the magnetic moment of the proton.

1944 **I. I. Rabi** (Columbia, New York): resonance method for recording the magnetic properties of atomic nuclei.

1945 **W. Pauli** (Zürich): discovery of the Exclusion Principle, also called the Pauli Principle.

1946 **P. W. Bridgman** (Harvard): invention of an apparatus to produce extremely high pressures and discoveries in the field of high-pressure physics.

1947 **E. V. Appleton** (London): physics of the upper atmosphere, especially the discovery of the so-called Appleton layer.

1948 **P. M. S. Blackett** (Manchester): development of the Wilson cloud chamber method and discoveries therewith in the field of nuclear physics and cosmic radiation.

1949 **H. Yukawa** (Kyoto): prediction of the existence of mesons on the basis of theoretical work on nuclear forces.

1950 **C. F. Powell** (Bristol): development of the photographic method of studying nuclear processes and discoveries regarding mesons made with this method.

1951 **J. D. Cockroft** (Harwell) and **E. T. S. Walton** (Dublin): pioneer work on the transmutation of atomic nuclei by artificially accelerated atomic particles.

1952 **F. Bloch** (Stanford) and **E. M. Purcell** (Harvard): development of new methods for nuclear magnetic precision measurements and discoveries in connection therewith.

1953 **F. Zernike** (Groningen): demonstration of the phase contrast method and invention of the phase contrast microscope.

1954 **M. Born** (Edinburgh): fundamental research in quantum mechanics, especially for the statistical interpretation of the wave function.

W. Bothe (Heidelberg): the coincidence method and discoveries made therewith.

1955 **W. E. Lamb** (Stanford): the fine structure of the hydrogen spectrum.

P. Kusch (Columbia, New York): precision determination of the magnetic moment of the electron.

1956 **W. Shockley** (Pasadena), **J. Bardeen** (Urbana) and **W. H. Brattain** (Murray Hill): investigations on semiconductors and discovery of the transistor effect.

1957 **T. Lee** (Columbia) and **C. Yang** (Princeton): penetrating investigation of the so-called parity laws, which has led to important discoveries regarding the elementary particles.

1958 **P. A. Cherenkov, I. M. Frank** and **I. E. Tamm** (Moscow): discovery and the interpretation of the Cherenkov effect.

1959 **E. Segrè** and **O. Chamberlain** (Berkeley): discovery of the antiproton.

1960 **D. A. Glaser** (Berkeley): invention of the bubble chamber.

1961 **R. Hofstadter** (Stanford): pioneering studies of electron scattering in atomic nuclei and discoveries concerning the structure of the nucleons.

R. L. Mössbauer (Munich): resonance absorption of gamma radiation and discovery of the effect which bears his name.

1962 **L. D. Landau** (Moscow): pioneering theories for condensed matter, especially liquid helium.

1963 **E. P. Wigner** (Princeton): the theory of the atomic nucleus and elementary particles, particularly through the discovery and application of fundamental symmetry principles.

Maria Goeppert-Mayer (La Jolla) and **J. H. D. Jensen** (Heidelberg): discoveries concerning nuclear shell structure.

1964 **C. H. Townes** (Massachusetts Institute of Technology), and **N. G. Basov** and **A. M. Prokhorov** (Moscow): fundamental work in the field of quantum electronics, which led to the construction of oscillators and amplifiers based on the maser-laser-principle.

1965 **S. Tomonaga** (Tokyo), **J. Schwinger** (Cambridge, Mass.,) and **R. P. Feynman** (California Institute of Technology, Pasadena): fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles.

1966 **A. Kastler** (Paris): discovery and development of optical methods for studying hertzian resonances in atoms.

1967 **H. A. Bethe** (Cornell): contributions to the theory of nuclear reactions, especially discoveries concerning the energy production in stars.

1968 **L. W. Alvarez** (Berkeley): decisive contributions to elementary particle physics, in particular the discovery of a large number of resonance states, made possible by the hydrogen bubble chamber technique and data analysis.

1969 **M. Gell-Mann** (California Institute of Technology, Pasadena): contributions and discoveries concerning the classification of elementary particles and their interactions.

1970 **H. Alfvén** (Stockholm): discoveries in magneto-hydrodynamics with fruitful applications in different parts of plasma physics.
L. Néel (Grenoble): discoveries concerning antiferromagnetism and ferrimagnetism which have led to important applications in solid state physics.

1971 **D. Gabor** (Imperial College, London): invention and development of the holographic method.

1972 **J. Bardeen** (Urbana), **L. N. Cooper** (Providence) and **J. R. Schrieffer** (Philadelphia): theory of superconductivity, usually called the BCS theory.

1973 **L. Esaki** (Yorktown Heights) and **I. Giaever** (Schenectady): experimental discoveries regarding tunnelling phenomena in semiconductors and superconductors respectively.
B. D. Josephson (Cambridge): theoretical predictions of the properties of a supercurrent through a tunnel barrier, in particular those phenomena which are generally known as the Josephson effects.

1974 **M. Ryle** and **A. Hewish** (Cambridge): pioneering research in radioastrophysics: Ryle for his observations and inventions, in particular of the aperture-synthesis technique, and Hewish for his decisive role in the discovery of pulsars.

1975 **A. Bohr** (Copenhagen), **B. Mottelson** (Copenhagen) and **J. Rainwater** (New York): discovery of the connection between collective motion and particle motion in atomic nuclei and the development of the theory of the structure of the atomic nucleus based on this connection.

1976 **B. Richter** (Stanford) and **S. C. C. Ting** (Massachusetts Institute of Technology): discovery of a heavy elementary particle of a new kind.

1977 **P. W. Anderson** (Murray Hill), **N. F. Mott** (Cambridge) and **J. H. van Vleck** (Harvard): fundamental theoretical investigations of the electronic structure of magnetic and disordered systems.

1978 **P. L. Kapitsa** (Moscow): basic inventions and discoveries in the area of low-temperature physics.
A. A. Penzias and **R. W. Wilson** (Holmdel): discovery of cosmic microwave background radiation.

1979 **S. L. Glashow** (Harvard), **A. Salam** (Imperial College, London) and **S. Weinberg** (Harvard): contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current.

1980 **J. W. Cronin** (Chicago) and **V. L. Fitch** (Princeton): discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons.

1981 **K. M. Siegbahn** (Uppsala): development of high-resolution electron spectroscopy.
N. Bloembergen (Harvard) and **A. L. Schawlow** (Stanford): development of laser spectroscopy.

1982 **K. G. Wilson** (Cornell): theory for critical phenomena in connection with phase transitions.

1983 **S. Chandrasekar** (Chicago): theoretical studies of the physical processes of importance to the structure and evolution of the stars.
W. A. Fowler (California Institute of Technology, Pasadena): theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the universe.

1984 **C. Rubbia** and **S. Van der Meer** (CERN, Geneva): decisive contributions to the discovery of the field particles W and Z, communicators of weak interaction.

1985 **K. von Klitzing** (Stuttgart): discovery of the quantized Hall effect.

1986 **E. Ruska** (Berlin): fundamental work in electron optics and the design of the first electron microscope.
G. Binning and **H. Rohrer** (Zurich): design of the scanning tunneling microscope.

1987 **G. Bednorz** and **K. A. Müller** (Zürich): for their important breakthrough in the discovery of superconductivity in ceramic materials.

1988 **L. Lederman** (Batavia, Illinois), **M. Schwartz** (Mountain View, California) and **J. Steinberger** (Geneva): for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino.

1989 **N. F. Ramsey** (Harvard): invention of the separated oscillatory fields method and its use in the hydrogen maser and other atomic clocks.
H. G. Dehmelt (University of Washington, Seattle) and **W. Paul** (Bonn): development of the ion trap technique.

1990 **J. I. Friedman** and **H. W. Kendall** (Massachusetts Institute of Technology) and **R. E. Taylor** (Stanford): pioneering investigations concerning deep elastic scattering of electrons on protons and bound neutrons, of essential importance for the development of the quark model in particle physics.

1991 **P.-G. de Gennes** (Collège de France, Paris): discovery that methods developed for studying order phenomena in simple systems can be generalized to more complex forms of matter, in particular to liquid crystals and polymers.

1992 **G. Charpak** (École Supérieure de Physique et Chemie, Paris, and CERN Geneva): invention and development of particle detectors, in particular the multiwire proportional chamber.

1993 **R. A. Hulse** and **J. H. Taylor** (Princeton): discovery of a new type of pulsar, that has opened up new possibilities for the study of gravitation.

1994 **B. N. Brockhouse** (McMaster University) and **C. G. Schull** (Massachusetts Institute of Technology): pioneering contributions to neutron scattering techniques for studies of condensed matter (namely neutron spectroscopy and neutron diffraction techniques, respectively).

1995 **M. L. Perl** (Stanford) and **F. Reines** (Irvine, California): pioneering experimental contributions to lepton physics (discovery of the tau particle and detection of the neutrino, respectively).

1996 **D. M. Lee** (Cornell), **D. D. Osheroff** (Stanford) and **R. C. Richardson** (Cornell): discovery of the superfluid phase of helium-3.

1997 **S. Chu** (Stanford), **C. Cohen-Tannoudji** (École Normal Supérieure, Paris) and **W. D. Phillips** (NIST, Gaithersburg): development of methods to cool and trap neutral atoms with laser light.