

# 1

## Basic Physical Data

### 1.1

#### Basic Physical Units

##### 1.1.1

#### SI Units

**Table 1.1** Fundamental and supplementary SI units.

Quantity	Unit	Abbreviation
<i>Fundamental Units</i>		
Amount of substance	mole	mol
Electrical current	ampere	A
Length	meter	m
Luminous intensity	candela	cd
Mass	kilogram	kg
Plane angle	radian	rad
Solid angle	steradian	sr
Temperature	Kelvin	K
Time	second	s
<i>Selected derived units</i>		
Capacitance	farad	F
Current density	ampere per square meter	A/m <sup>2</sup>
Electrical charge	coulomb	C
Electric potential	volt	V
Electrical resistance	ohm	Ω
Energy	joule	J
Frequency	hertz	Hz
Force	newton	N
Inductance	henry	H
Magnetic flux	weber	Wb
Magnetic flux density	tesla	T
Power	watt	W

**Table 1.2** Standard prefixes for SI units.

Prefix	Symbol	Factor	Prefix	Symbol	Factor
yotta	Y	$10^{24}$	deci	d	$10^{-1}$
zetta	Z	$10^{21}$	centi	c	$10^{-2}$
exa	E	$10^{18}$	milli	m	$10^{-3}$
peta	P	$10^{15}$	micro	$\mu$	$10^{-6}$
tera	T	$10^{12}$	nano	n	$10^{-9}$
giga	G	$10^9$	pico	p	$10^{-12}$
mega	M	$10^6$	femto	f	$10^{-15}$
kilo	k	$10^3$	atto	a	$10^{-18}$
hecto	h	$10^2$	zepto	z	$10^{-21}$
deca	da	$10^1$	yocto	y	$10^{-24}$

## 1.1.2

**cgs-Gaussian Units**

For a useful overview of non-SI units, see [1].

**Table 1.3** Comparison of SI and cgs units.

Quantity	Unit	Abbrev.	SI equivalent
Length	centimeter	cm	$10^{-2}$ m
Mass	gramme	g	$10^{-3}$ kg
Time	second	s	1 s
Force	dyne	dyn	$10^{-5}$ N
Energy	erg	erg	$10^{-7}$ J
Power	erg per second	erg s $^{-1}$	$10^{-7}$ W
Electrical charge	statcoulomb	statcoul	$(3 \times 10^9)^{-1}$ C
Current	statampere	statamp	$(3 \times 10^9)^{-1}$ A
Electric potential	statvolt	statvolt	300 V
Magnetic flux density	gauss	G	$10^{-4}$ T

## 1.2

**Maxwell's Electromagnetic Equations****Table 1.4** Maxwell's equations.

	SI	cgs-Gaussian	
$\nabla \times E$	$= -\frac{\partial B}{\partial t}$	$= -\frac{1}{c} \frac{\partial B}{\partial t}$	Faraday's law
$\nabla \times H$	$= \frac{\partial D}{\partial t} + J$	$= \frac{1}{c} \frac{\partial D}{\partial t} + \frac{4\pi}{c} J$	Ampere's law

Table 1.4 (continued)

	SI	cgs-Gaussian	
$\nabla \cdot \mathbf{D}$	$= \rho_c$	$= 4\pi\rho_c$	Poisson equation
$\nabla \cdot \mathbf{B}$	$= 0$	$= 0$	
$\mathbf{D}$	$= \epsilon_r \epsilon_0 \mathbf{E}$	$= \epsilon_r \mathbf{E}$	
$\mathbf{B}$	$= \mu_r \mu_0 \mathbf{H}$	$= \mu_r \mathbf{H}$	

**Boundary conditions** The boundary conditions at an interface for Maxwell's electromagnetic equations are that the tangential component of  $\mathbf{E}$ , and the normal component of  $\mathbf{B}$ , must each be continuous, where normal means parallel to the local normal vector to the interface, and tangential means in the plane perpendicular to the local normal.

### 1.3

#### Special Relativity

Assume standard inertial frames  $S$  and  $S'$ , with respective Cartesian coordinates  $(x, y, z)$ ,  $(x', y', z')$  aligned such that the origins  $O, O'$  are coincident at time  $t = t' = 0$ , with  $S'$  moving with velocity  $\mathbf{v}$  with respect to  $S$ . Subscript  $\parallel$  will denote the direction of this mutual motion, and subscript  $\perp$  denotes the orthogonal plane. The Lorentz transformations of various physically significant quantities are given in the following table [2]:

Table 1.5 Lorentz transformations.

Quantity	Transformation
Space-time	$\mathbf{r} = \gamma_v (\mathbf{r}'_{\parallel} + \mathbf{v}t') + \mathbf{r}'_{\perp}$ $t = \gamma_v (t' + v r'_{\parallel}/c^2)$
Invariant	$r^2 - c^2 t^2$
Velocity	$\mathbf{u} = (\mathbf{u}'_{\parallel} + \mathbf{v} + \mathbf{u}'_{\perp}/\gamma_v) / (1 + u'_{\parallel} v/c^2)$
Momentum-mass	$\mathbf{p} = \gamma_v (\mathbf{p}'_{\parallel} + m' \mathbf{v}) + \mathbf{p}'_{\perp}$ $mc = \gamma_v (m'c + v p'_{\parallel}/c)$
Invariant	$p^2 - m^2 c^2$
Current and charge densities	$\mathbf{J} = \gamma_v (\mathbf{J}'_{\parallel} + v \rho'_c) + \mathbf{J}'_{\perp}$ $\rho_c = \gamma_v (\rho'_c + v J'_{\parallel}/c^2)$
Invariant	$J^2 - c^2 \rho_c^2$
Electric and magnetic fields	$\mathbf{E} = \mathbf{E}'_{\parallel} + \gamma_v (\mathbf{E}'_{\perp} - \mathbf{v} \times \mathbf{B}')$ $\mathbf{B} = \mathbf{B}'_{\parallel} + \gamma_v (\mathbf{B}'_{\perp} + \mathbf{v} \times \mathbf{E}'/c^2)$

## 1.4 Physical Constants

The values of the constants quoted here are the 2006 CODATA recommended values [3].

**Table 1.6** Values of physical constants.

Quantity	Symbol	Value	Units
Speed of light in vacuum	$c$	299 792 458	$\text{m s}^{-1}$
Magnetic constant	$\mu_0$	$4\pi \times 10^{-7}$	$\text{H m}^{-1}$
Electric constant	$\epsilon_0$	$8.854 187 817 \dots \times 10^{-12}$	$\text{F m}^{-1}$
Vacuum impedance	$Z_0$	376.730 313 461 ...	$\Omega$
Gravitational constant	$G$	$6.674 28(67) \times 10^{-11}$	$\text{m}^3 \text{kg}^{-1} \text{s}^{-2}$
Planck constant	$h$	$6.626 068 96(33) \times 10^{-34}$	J s
Planck mass	$m_{\mathcal{P}}$	$2.176 44(11) \times 10^{-8}$	kg
Planck length	$l_{\mathcal{P}}$	$1.616 252(81) \times 10^{-35}$	m
Planck time	$t_{\mathcal{P}}$	$5.391 24(27) \times 10^{-44}$	s
Avogadro constant	$N_A$	$6.022 141 79(30) \times 10^{23}$	$\text{mol}^{-1}$
Bohr magneton	$\mu_B$	$927.400 915(23) \times 10^{-26}$	$\text{J T}^{-1}$
Bohr radius	$a_0$	$0.529 177 208 59(36) \times 10^{-10}$	m
Boltzmann constant	$k_B$	$1.380 650 4(24) \times 10^{-23}$	$\text{J K}^{-1}$
Elementary charge	$e$	$1.602 176 487(40) \times 10^{-19}$	C
Fine structure constant	$\alpha$	$7.297 352 537 6(50) \times 10^{-3}$	
	$\alpha^{-1}$	137.035 999 679(94)	
Molar gas constant	$R$	8.314 472(15)	$\text{J mol}^{-1} \text{K}^{-1}$
Nuclear magneton	$\mu_N$	$5.050 783 24(13) \times 10^{-27}$	$\text{J}^{-1}$
Rydberg constant	$R_\infty$	10 973 731.568 527(73)	$\text{m}^{-1}$
Stefan–Boltzmann constant	$\sigma$	$5.670 400(40) \times 10^{-8}$	$\text{W m}^{-2} \text{K}^{-4}$
Thomson cross section	$\sigma_e$	$0.665 245 855 8(27) \times 10^{-28}$	$\text{m}^2$
Wien constant	$b$	$2.897 768 5(51) \times 10^{-3}$	m K
<b><math>\alpha</math> Particle:</b>			
Mass	$m_\alpha$	$6.644 656 20(33) \times 10^{-27}$	kg
– electron mass ratio	$m_\alpha / m_e$	$7.294 299 536 5(31) \times 10^3$	
– proton mass ratio	$m_\alpha / m_p$	3.972 599 689 51(41)	
<b>Deuteron:</b>			
Mass	$m_d$	$3.343 583 20(17) \times 10^{-27}$	kg
– electron mass ratio	$m_d / m_e$	$3.670 482 965 4(16) \times 10^3$	
– proton mass ratio	$m_d / m_p$	1.999 007 501 08(22)	
magnetic moment	$\mu_d$	$4.330 734 65(11) \times 10^{-27}$	$\text{J T}^{-1}$

Table 1.6 (continued)

Quantity	Symbol	Value	Units
<b>Electron:</b>			
Mass	$m_e$	$9.109\,382\,15(45) \times 10^{-31}$	kg
– $\alpha$ particle mass ratio	$m_e/m_\alpha$	$1.370\,933\,561\,1(29) \times 10^{-4}$	
– proton mass ratio	$m_e/m_p$	$5.446\,170\,217\,7(24) \times 10^{-4}$	
– deuteron mass ratio	$m_e/m_d$	$2.724\,437\,117\,0(58) \times 10^{-4}$	
– neutron mass ratio	$m_e/m_n$	$5.438\,673\,445\,9(33) \times 10^{-4}$	
Magnetic moment	$\mu_e$	$-928.476\,377(23) \times 10^{-26}$	J T <sup>-1</sup>
Charge to mass ratio	$-e/m_e$	$-1.758\,820\,150(44) \times 10^{11}$	C kg <sup>-1</sup>
Classical radius	$r_e$	$2.817\,940\,289\,4(58) \times 10^{-15}$	m
<b>Helion (<sup>3</sup>He nucleus):</b>			
Mass	$m_h$	$5.006\,411\,92(25) \times 10^{-27}$	kg
– electron mass ratio	$m_h/m_e$	$5.495\,885\,276\,5(52) \times 10^3$	
– proton mass ratio	$m_h/m_p$	$2.993\,152\,671\,3(26)$	
<b>Neutron:</b>			
Mass	$m_n$	$1.674\,927\,211(84) \times 10^{-27}$	kg
– electron mass ratio	$m_n/m_e$	$1.838\,683\,660\,5(11) \times 10^3$	
– proton mass ratio	$m_n/m_p$	$1.001\,378\,419\,18(46)$	
Magnetic moment	$\mu_n$	$-0.966\,236\,41(23) \times 10^{-26}$	J T <sup>-1</sup>
<b>Proton:</b>			
Mass	$m_p$	$1.672\,621\,637(83) \times 10^{-27}$	kg
– electron mass ratio	$m_p/m_e$	$1.836\,152\,672\,47(80) \times 10^3$	
– neutron mass ratio	$m_p/m_n$	$0.998\,623\,478\,24(46)$	
Magnetic moment	$\mu_p$	$1.410\,606\,662(37) \times 10^{-26}$	J T <sup>-1</sup>

## 1.5

## Dimensional Analysis

Table 1.7 Dimensions of common variables.

	SI		Quantity		cgs
C	$\frac{q^2 t^2}{l^2 m}$	F	capacitance	$l$	cm
q	$q$	C	charge	$\frac{l^{3/2} m^{1/2}}{t}$	statcoul
$\rho_c$	$\frac{q}{l^3}$	C m <sup>-3</sup>	charge density	$\frac{m^{1/2}}{l^{3/2} t}$	statcoul cm <sup>-3</sup>
S	$\frac{q^2 t}{l^2 m}$	S	conductance	$\frac{l}{t}$	cm s <sup>-1</sup>
$\sigma_c$	$\frac{q^2 t}{l^3 m}$	S m <sup>-1</sup>	conductivity	$\frac{l}{t}$	s <sup>-1</sup>
I	$\frac{q}{t}$	A	current	$\frac{l^{3/2} m^{1/2}}{t^2}$	statamp
J	$\frac{q}{l^2 t}$	A m <sup>-2</sup>	current density	$\frac{m^{1/2}}{l^{1/2} t^2}$	statamp cm <sup>-2</sup>
D	$\frac{q}{l^2}$	C m <sup>-2</sup>	displacement	$\frac{m^{1/2}}{l^{1/2} t}$	statcoul cm <sup>-2</sup>

Table 1.7 (continued)

	SI	Quantity	cgs		
$\eta_v$	$\frac{m}{lt}$	$\text{kg m}^{-1} \text{s}^{-1}$	dynamic viscosity	$\frac{m}{lt}$	P
$E$	$\frac{mI}{qt^2}$	$\text{V m}^{-1}$	electric field	$\frac{m^{1/2}I^{1/2}}{t}$	statvolt $\text{cm}^{-1}$
$\phi$	$\frac{l^2 m}{qt^2}$	V	electric potential	$\frac{m^{1/2}}{l^{1/2}t}$	statvolt
$\mathcal{E}$	$\frac{mI^2}{t^2}$	J	energy	$\frac{mI^2}{t^2}$	erg
$\varepsilon$	$\frac{m}{lt^2}$	$\text{J m}^{-3}$	energy density	$\frac{m}{lt^2}$	erg $\text{cm}^{-3}$
$F$	$\frac{Im}{t^2}$	N	force	$\frac{Im}{t^2}$	dyn
$\nu$	$\frac{1}{t}$	Hz	frequency	$\frac{1}{t}$	Hz
$L$	$l$	m	length	$l$	cm
$\Phi$	$\frac{l^2 m}{qt}$	Wb	magnetic flux	$\frac{l^{3/2} m^{1/2}}{t}$	Mx
$B$	$\frac{m}{qt}$	T	magnetic flux density	$\frac{m^{1/2}}{l^{1/2}t}$	G
$H$	$\frac{q}{lt}$	$\text{A m}^{-1}$	magnetic intensity	$\frac{m^{1/2}}{l^{1/2}t}$	Oe
$\mu$	$\frac{l^2 q}{t}$	$\text{J T}^{-1}$	magnetic moment	$\frac{l^{5/2} m^{1/2}}{t}$	Oe $\text{cm}^3$
$m$	$m$	kg	mass	$m$	gram
$\rho$	$\frac{m}{l^3}$	$\text{kg m}^{-3}$	mass density	$\frac{m}{l^3}$	$\text{gm cm}^{-3}$
$P$	$\frac{l^2 m}{t^3}$	W	power	$\frac{l^2 m}{t^3}$	erg $\text{s}^{-1}$
$p$	$\frac{m}{lt^2}$	P	pressure	$\frac{m}{lt^2}$	dyn $\text{cm}^{-2}$
$R$	$\frac{l^2 m}{q^2 t}$	$\Omega$	resistance	$\frac{t}{l}$	$\text{s cm}^{-1}$
$\eta$	$\frac{l^3 m}{q^2 t}$	$\Omega \text{ m}$	resistivity	$t$	s
$\kappa$	$\frac{Im}{t^3}$	$\text{W m}^{-1} \text{K}^{-1}$	thermal conductivity	$\frac{Im}{t^3}$	erg $\text{cm}^{-1} \text{s}^{-1} \text{K}^{-1}$
$\mu_0$	$\frac{Im}{q^2}$	$\text{H m}^{-1}$	vacuum permeability		
$\epsilon_0$	$\frac{q^2 t^2}{l^3 m}$	$\text{F m}^{-1}$	vacuum permittivity		
$A$	$\frac{Im}{qt}$	$\text{Wb m}^{-1}$	vector potential	$\frac{l^{1/2} m^{1/2}}{t}$	G cm
$u$	$\frac{l}{t}$	$\text{m s}^{-1}$	velocity	$\frac{l}{t}$	$\text{cm s}^{-1}$

## 1.6

### Ionization Energies of Gas-Phase Atoms and Molecules

The energies of first ionization  $E_i$  for certain gas-phase molecules are given here, selected from [4]

Table 1.8 Ionization energies of gas-phase atoms and molecules

Substance	Formula	$E_i/\text{eV}$
Acetylene	$\text{C}_2\text{H}_2$	11.400
Ammonia	$\text{NH}_3$	10.070
Argon	Ar	15.759 62

Table 1.8 (continued)

Substance	Formula	$E_i/eV$
Boron	B	8.298 03
Calcium	Ca	6.113 16
Carbon dioxide	CO <sub>2</sub>	13.773
Carbon monoxide	CO	14.014
Chlorine	Cl	12.967 64
Chlorine	Cl <sub>2</sub>	11.480
Chlorosilane	ClH <sub>3</sub> Si	11.4
Cyanide	CN	13.598 4
Disodium	Na <sub>2</sub>	4.894
Ethylene	C <sub>2</sub> H <sub>4</sub>	10.513 8
Fluorine (atomic)	Fl	17.422
Fluorine	Fl <sub>2</sub>	15.697
Formaldehyde	CH <sub>2</sub> O	10.88
Formic acid	CH <sub>2</sub> O <sub>2</sub>	11.33
Helium	He	24.587 41
Hydrogen (atomic)	H	13.598 44
Hydrogen	H <sub>2</sub>	15.425 93
Hydrogen chloride	HCl	12.749
Hydrogen sulfide	H <sub>2</sub> S	10.457
Hydroxyl	HO	13.017 0
Krypton	Kr	13.999 961
Mercury	Hg	10.437 50
Methane	CH <sub>4</sub>	12.61
Methanol	CH <sub>3</sub> OH	10.85
Methyl	CH <sub>3</sub>	9.843
Methylene	CH <sub>2</sub>	10.396
Neon	Ne	21.564 54
Nitrogen	N	14.534 14
Nitrogen	N <sub>2</sub>	15.580 8
Oxygen	O	13.618 06
Oxygen	O <sub>2</sub>	12.069 7
Silane	SiH <sub>4</sub>	11.00
Silicon	Si	8.151 69
Sodium	Na	5.139 08
Tetrachloromethane	CCL <sub>4</sub>	11.47
Tetrachlorosilane	SiCl <sub>4</sub>	11.79
Water	H <sub>2</sub> O	12.620 6
Xenon	Xe	12.129 87

## 1.7

**Electron Affinities of Selected Atoms and Molecules**

The electron affinity  $E_A$  is defined to be the energy difference between the ground state of the neutral, and the lowest energy state of the corresponding negative ion. If  $E_A > 0$ , then the negative ion is stable; if  $E_A < 0$ , the negative ion is unstable. Selected data is presented below, drawn from [4, 5]

**Table 1.9** Electron affinities of selected atoms and molecules.

Substance	Formula	$E_i/\text{eV}$
Aluminum	Al	0.432 8
Argon	Ar	–
Beryllium	Be	–
Boron	B	0.279 7
Calcium	Ca	0.024 55
Carbon	C	1.262
Chlorine (atomic)	Cl	3.613
Chromium	Cr	0.675 84
Cobalt	Co	0.663 3
Copper	Cu	1.235
Deuterium	D	0.745 6
Fluorine (atomic)	F	3.401
Helium	He	–
Hydrogen	H	0.7541
Iron	Fe	0.151
Krypton	Kr	–
Lithium	Li	0.618 0
Magnesium	Mg	–
Manganese	Mn	–
Nickel	Ni	1.157 16
Nitrogen (atomic)	N	–
Neon	Ne	–
Oxygen (atomic)	O	1.461
Phosphorus	P	0.746 5
Potassium	K	0.501 459
Scandium	Sc	0.188
Silicon	Si	1.390
Sodium	Na	0.547 9
Sulfur	S	2.077
Titanium	Ti	0.084
Tritium	T	0.754 8
Vanadium	V	0.525
Xenon	Xe	–



Table 1.9 (continued)

Substance	Formula	$E_i/\text{eV}$
<i>Diatomic molecules</i>		
Carbon	$\text{C}_2$	3.27
Chlorine	$\text{Cl}_2$	2.28
Cyanide	CN	3.862
Fluorine	$\text{F}_2$	3.01
Methylidine radical	CH	1.238
Oxygen	$\text{O}_2$	0.450
Disilicon	$\text{Si}_2$	2.201
	SiH	1.277
	TiO	1.30
<i>Triatomic molecules</i>		
Ozone	$\text{C}_3$	1.981
	$\text{CCl}_2$	1.593
	$\text{CF}_2$	0.180
	$\text{CH}_2$	0.652
	$\text{C}_2\text{O}$	2.311
	$\text{O}_3$	2.103
	$\text{SiF}_2$	0.10
	$\text{Si}_2\text{F}$	1.99
	$\text{SiH}_2$	1.124
	$\text{Si}_2\text{H}$	2.31
$\text{Si}_3$	2.29	
Titanium dioxide	$\text{TiO}_2$	1.59
Water	$\text{H}_2\text{O}$	1.078

## 1.8

### Atomic and Molecular Notation

#### 1.8.1

##### Atomic Electron Configurations

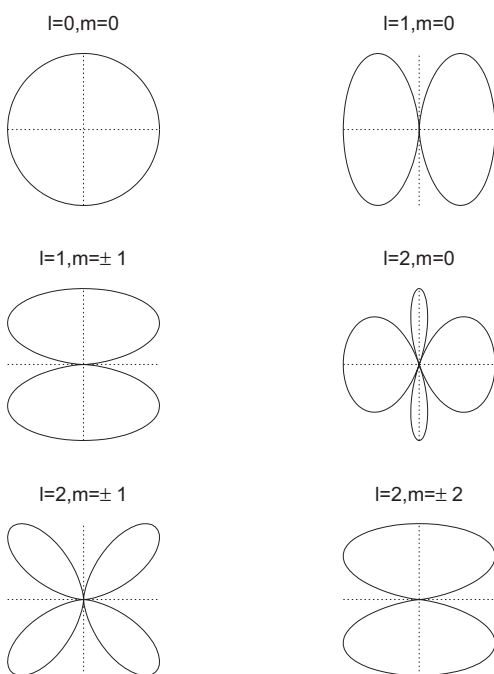
The electronic configuration in atoms is characterized by four quantum numbers ( $n$ ,  $l$ ,  $m_l$ ,  $m_s$ ) that define the distribution of electrons across the available atomic levels and orbitals, with no two electrons allowed to share the same four quantum numbers (the Pauli Principle). The classification is arranged in descending significance in terms of energy contribution.

### 1.8.1.1 Principal Quantum Number, $n$

Levels are denoted by the principal quantum number,  $n$ , which can take integer values  $n = 1, 2, 3 \dots$  and which is the main determinant of electron energy. Atomic states with different  $n$  have significantly different energies. Historical notation for the principal quantum number is  $K(n = 1)$ ,  $L(n = 2)$ ,  $M(n = 3)$  and so on, alphabetically (a notation usually used in X-ray spectra). For each value of  $n$ , there are  $n$  subshells, identified by the angular momentum (or azimuthal) quantum number  $l$ .

### 1.8.1.2 Azimuthal Quantum Number, $l$

Each subshell or sublevel (sometimes referred to as orbital) is denoted by the angular momentum (or azimuthal) quantum number  $l$ , which can take integer values from 0 to  $n-1$ . These refer to the quantization of the orbital angular momentum of an electron in the subshell, and leads to the overall shape of the orbital (see Figure 1.1). A conventional notation for the first four  $l$ -values is  $s(l = 0)$ ,  $p(l = 1)$ ,  $d(l = 2)$  and  $f(l = 3)$ ; the notation continues alphabetically with  $g(l = 5)$  and so on. Each subshell can contain a maximum of  $2(2l + 1)$  electrons, which can occupy states characterized by  $m_l$  and  $m_s$ .



**Figure 1.1** The angular dependence of the  $s$ ,  $p$  and  $d$  orbitals, showing symmetry about the principal (horizontal) axis.

### 1.8.1.3 Magnetic Quantum Number, $m_l$

Given that an electron is in subshell  $l$ , its angular momentum component along the principal axis (the main symmetry axis for the wavefunctions) is further quantized by the magnetic quantum number  $m_l$ , which can take integer values in the range  $(-l, -l + 1, \dots, 0, \dots, l - 1, l)$ , yielding  $2l + 1$  states in total.

### 1.8.1.4 Spin Quantum Number, $m_s$

Finally, there are two spin states for each electron in any  $n, l, m_l$  state: spin-up and spin-down, corresponding to  $m_s = \pm \frac{1}{2}$ .

As a consequence of the distribution of electrons across the possible angular momentum, magnetic and spin quantum states, the total number of electrons in each of the principal quantum levels is  $2n^2$ , as can be seen from Table 1.10. In the standard notation for the configuration of electrons in an atom, each shell and subshell is given as a character string, with the number of electrons in each subshell stated as a superscript on the  $l$  value: for example, the configuration of electrons in He can be stated as  $1s^2$ ; for Carbon atoms,  $1s^2 2s^2 2p^2$ , and so on. The ground-state configuration of selected atoms is given in Table 1.11.

**Table 1.10** Atomic notation: under each principal quantum number, the subshells are denoted, along with the number of electrons per subshell.

	$n = 1$	(K)	$n = 2$	(L)	$n = 3$	(M)	$n = 4$	(N)	$n = 5$	(O)
$l = 0$	1s	2	2s	2	3s	2	4s	2	5s	2
$l = 1$			2p	6	3p	6	4p	6	5p	6
$l = 2$					3d	10	4d	10	5d	10
$l = 3$							4f	14	5f	14
$l = 4$									5g	18
Total		2		8		18		32		50

**Table 1.11** Electronic configuration of ground states for selected atoms.

Atom	Ground state	Comment
H	1s	
He	$1s^2$	filled K shell
Li	$1s^2 2s$	filled K shell
Be	$1s^2 2s^2$	filled K shell
B	$1s^2 2s^2 2p$	filled K shell
C	$1s^2 2s^2 2p^2$	filled K shell
N	$1s^2 2s^2 2p^3$	filled K shell
O	$1s^2 2s^2 2p^4$	filled K shell
F	$1s^2 2s^2 2p^5$	filled K shell
Ne	$1s^2 2s^2 2p^6$	filled K, L shells
Na	[Ne]3s	filled K, L shells
Si	[Ne]3s <sup>2</sup> 3p <sup>2</sup>	filled K, L shells
Ar	[Ne]3s <sup>2</sup> 3p <sup>6</sup>	filled K, L, M shells

**Table 1.12** Selected significant spectral lines of atomic and singly ionized elements, as observed in air, and chosen for the greatest relative intensity; \* denotes Fraunhofer lines.

Element	Description	Transition	Lines/nm
Ar	prominent lines	4s–4p	696.54, 706.72
ArII	prominent visible	4s–4p	472.69, 4879.86
CaII	H, K	4s–4p	393.36, 396.85*
ClII	prominent visible	4s–4p(1st 4), 3d–4p	479.45, 489.68, 490.48, 521.80, 542.32
Fe	prominent visible	4s <sup>2</sup> –4s4p	385.992, 404.582, 438.356*
H	Lyman Series	$n = 2, 3, \dots \rightarrow 1$	121.5( $\alpha$ ), 102.5( $\beta$ ), 97.2( $\gamma$ ), 94.9( $\delta$ ) ... 91.12
H	Balmer Series	$n = 3, 4, \dots \rightarrow 2$	656.3( $\alpha$ ), 486.1( $\beta$ ), 434.1( $\gamma$ ), 410.2( $\delta$ ) ... 634.6*
H	Paschen Series	$n = 4, 5, \dots \rightarrow 3$	1870, 1280, 1090, 1020, 954 ... 820
He	prominent visible	2p–4d, 2s–2p, 2p–3d	447.15, 501.57, 587.56, 667.81*
Na	D <sub>2</sub> , D <sub>1</sub>	3s–3p	588.997, 589.594*
O	prominent visible		615.60, 615.68, 615.82
OII	prominent visible		391.19, 397.32, 407.59, 441.49, 464.18, 464.91

Atomic spectra arise when electrons make the transition from one set of ( $n$ ,  $l$ ,  $m_l$ ,  $m_s$ ) to another, losing energy by emission of photons (or gaining energy by absorption). Examples of important spectra are given in Table 1.12.

### 1.8.1.5 Multielectron Atoms

For atoms with several electrons [6], there is strong electrostatic coupling between the orbital angular momentum and the spins across the populated states, leading to additional energy structure in the electronic configuration.

The total resultant orbital angular momentum vector arising from the  $l_i$  of the electrons in the atom is a quantum vector denoted as  $L$ . The underlying quantization comes from the interaction of electrons with different values of  $n$  and  $l$ , and is expressed in the quantum-mechanical vector addition of the associated vector angular momenta  $l_i$  to produce a resultant total orbital angular momentum  $L$ , the possible quantized values of which are given by  $m_l$ . In a similar way, the resultant of the quantum spins over the  $m_{s,i}$  is designated by  $S$ . These resultants,  $L$  and  $S$ , can be added to produce a total resultant angular momentum  $J$  of the electrons in the atom, which is also quantized. The magnitude of the quantized resultant of  $L$  and  $S$  can only take the values  $L + S$ ,  $L + S - 1$ , ...,  $|L - S|$ , denoted by  $J$  (this is a general rule for all quantum vectors).

The states  $L = 0, 1, 2, 3, \dots$  are labeled  $S, P, D, F$  by analogy with the  $l$  values, with the series continuing alphabetically beyond  $L = 4$ . (Note that electrons in closed shells do not contribute to this coupling.) An additional fine-structure arises in each  $L$ -state, when magnetic interactions (from the intrinsic dipole moments of the electrons) are taken into account. States that are formed in this way are deemed to have multiplicity  $2S + 1$  and form multiplet states, designated by the  $L$  value letter, with left superscript showing the multiplicity of the state, and right subscript giving the corresponding  $J$  value.

For example, if an atom has an  $f$ -electron ( $l = 3$ ) and a  $d$ -electron ( $l = 2$ ), then the possible values of  $L$  are  $3 + 2 = 5, 4, 3, 2$  and  $|3 - 2| = 1$ . In a similar way, the possible values of  $S$  are 0 and 1. Hence, the multiplet states are  $P, D, F, G$  and  $H$ , each of which can have  $S = 0$  (with multiplicity 1, and therefore are singlet states) or  $S = 1$  (with multiplicity 3, and so are triplet states). The singlet states are then  ${}^1P_1(L = 1, S = 0, J = 1), {}^1D_2(L = 2, S = 0, J = 2)$  and so on, with the triplet states as  ${}^3P_2(L = 1, S = 1, J = 2), {}^3D_3(L = 2, S = 1, J = 3)$  and so on.

### 1.8.1.6 Selection Rules for Transitions

For electric dipole transitions, the following rules apply:

1.  $\Delta n$  unrestricted
2.  $\Delta l = \pm 1$
3.  $\Delta L = 0, \pm 1$  except  $0 \leftrightarrow 0$
4.  $\Delta S = 0$
5.  $\Delta J = 0, \pm 1$  except  $0 \leftrightarrow 0$

### 1.8.1.7 Emission and Absorption

The spectral emission coefficient  $\varepsilon(\nu)$  due to a spontaneous electronic transition from an upper state  $u$  to a lower state  $l$  in an atom resulting in the emission of a photon of frequency  $\nu$  is given by

$$\varepsilon = \frac{n_u A_{ul}}{4\pi} h\nu \Phi(\nu - \nu_0) \quad (1.1)$$

where  $n_u$  is the population of the upper level,  $A_{ul}$  is the Einstein coefficient for spontaneous emission,  $\nu_0$  is the line center defined by  $h\nu_0 = E_u - E_l$ , where  $E_{u,l}$  denotes the energy level of the upper and lower atomic states, and  $\Phi$  is the line-shape function, which describes natural and instrumental line-broadening mechanisms.

In the case of electric dipole transitions,  $A_{ul}$  is defined to be

$$A_{ul} = \frac{64\pi^4 \nu^3}{3\epsilon_0 h c^3} \mu_{ul}^2 \quad (1.2)$$

where  $\mu_{ul}$  is the transition dipole moment.

## 1.8.2

### Molecular Electron Configurations

The configurations of electrons in molecules is more complicated than the single atom case because the nuclear motion of the constituent species influences the electron energy levels, along with the persistent internuclear electric field that bonds the molecule together [7, 8].

The ground electronic state of a molecule is designated by  $X$ , with excited states of the same multiplicity (i.e., spin quantum number in Section 1.8.2.3) as the

ground state denoted by  $A, B, C, \dots$  in ascending order of energy; if excited states have a different multiplicity from the ground state, then these states are labeled with lower-case letters  $a, b, c, \dots$ . The details of the electronic configurations in such states is given in the following paragraphs, which apply mainly to diatomic molecules.

### 1.8.2.1 Born–Oppenheimer Approximation

The Born–Oppenheimer approximation separates out the nuclear motion (vibration and rotation) from the electron behavior, under the assumption that the electrons will move much faster than the heavier nuclei. This assumption means that the electronic transition energies  $E_{\text{el}}$  (a few eV) are taken to be much larger than the vibrational energies  $E_{\text{vib}}$  (around 0.1 eV), which in turn are much larger than the rotational energies  $E_{\text{rot}}$  (a few meV):

$$E_{\text{el}} \gg E_{\text{vib}} \gg E_{\text{rot}} \quad (1.3)$$

### 1.8.2.2 $\Lambda$ Quantum Number

Assuming that the Born–Oppenheimer approximation (Section 1.8.2.1) holds, the electronic configuration is characterized in a similar way to atomic electrons in that the quantum numbers ( $n_1, l_1, n_2, l_2, \dots$ ) produce different quantized energy levels associated with the quantum vectors  $L, S$  and  $J$ ; however, the quantizing axis is the internuclear one, and the resultant orbital angular momentum along this axis is designated  $\Lambda$ , with states  $\Lambda = 0, 1, 2, \dots$  given the notation  $\Sigma, \Pi, \Delta$  and so on, analogous with the  $S, P, D$  atomic  $L$  states.

### 1.8.2.3 Spin Quantum Number

Coupling of electron spins to the internuclear axis is weak, and so the resultant (total)  $S$  is much the same as for atoms; however,  $S$ , the axial component of  $S$  (and not to be confused with the Greek letter indicating the  $\Lambda$  value), plays a key role in diatomic molecules, coupling to  $\Lambda$  to form a resultant  $\Omega$ , the total electronic angular momentum along the internuclear axis.  $\Omega = |\Lambda + S|$ , in a similar way to  $J$  for atoms. Hence,  $\Omega$  can take the values  $\Lambda + S, \Lambda + S - 1, \dots, |\Lambda - S|$ , and such states are deemed to have a (spin) multiplicity  $2S + 1$  (known as spin-splitting). Each such state can be subdivided into two  $\Lambda$ -substates, giving a total degeneracy of  $(2S + 1)(2 - \delta_{0,\Lambda})$  where  $\delta_{i,j} = 1$  if  $i = j$  and 0 otherwise, is the Kronecker delta.

### 1.8.2.4 Molecular Term Notation

The molecular notation then is as follows: the  $\Lambda$  state is written with a left superscript denoting the associated multiplicity of the of  $\Sigma$  value, and a right subscript giving the maximum  $\Omega$  value. Hence, a state with  $S = 0, \Lambda = 0$  is written as  $^1\Sigma$  (see Table 1.13); for the state with  $S = 1, \Lambda = 1$  (and therefore,  $\Omega = 2$ ) is written by  $^3\Pi_2$ . This notation is preceded by a letter denoting the multiplicity of the state:  $X$  is ground state, and multiplicities are given by  $A, B, C$  if they have the same multiplicity as the ground state, otherwise lower case letters are used.

**Table 1.13** Molecular electronic state notation, showing the associated quantum numbers and electron degeneracy  $g$ .

Term	State		$g$
$^1\Sigma$	singlet sigma	$S = 0, \Lambda = 0$	1
$^2\Pi$	doublet pi	$S = 1/2, \Lambda = 1$	4
$^3\Sigma$	triplet sigma	$S = 1, \Lambda = 0$	3
$^3\Pi$	triplet pi	$S = 1, \Lambda = 1$	6
$^2\Delta$	doublet delta	$S = 1/2, \Lambda = 3$	4

### 1.8.2.5 Symmetry

The symmetry of the electron orbitals is a further complication: for a homonuclear molecule, the electron density must be symmetric with respect to the midpoint between the nuclei (that is, the center of mass), but the wavefunction of the electron can be even or odd parity, denoted  $g$  or  $u$ , respectively (from the German *gerade* and *ungerade*). For  $\Sigma$  states, symmetry of the wavefunction with respect to a mirror reflection through a plane containing the internuclear axis is denoted by a right superscript  $+$  if symmetric;  $-$  if not.

### 1.8.2.6 Selection Rules for Transitions

Electric dipole transitions between electronic levels in diatomic molecules obey the following selection rules:

1.  $\Delta\Sigma = 0$  (no change in total electron spin)
2.  $\Delta\Lambda = 0, \pm 1$
3.  $u \leftrightarrow g$
4.  $\Sigma^+ \leftrightarrow \Sigma^+$  or  $\Sigma^- \leftrightarrow \Sigma^-$

The spectra of molecules is considerably more complex than that of atoms because of the more extensive range of possible transitions. Molecular spectra consist of bands, which are very tightly grouped series of emission (or absorption) lines within an amplitude envelope that may extend only for a few nanometers. The spacing of the lines within the band head is controlled by electron transitions between the molecule's rotational states. The envelopes are not symmetric: the conspicuous sharp edge is termed the band head, with the envelope fading smoothly in amplitude towards increasing wavelength (termed 'degraded to red') or decreasing wavelength ('degraded to violet').

Certain molecules exhibit very extensive band systems that span wide spectral ranges with little variation in band intensity or structure, such as  $\text{H}_2$  (more than 100 strong bands between 406 and 835 nm),  $\text{Cl}_2$  (mixture of continuum and band emission in 480–600 nm, strong continuous absorption in 250–400 nm), CO (198–860 nm, including third positive, Asundi, triplet, Cameron, 3A, Knauss & Kaplan bands, in addition to those in Table 1.14).

**Table 1.14** Selected significant molecular spectral bands, as observed in air, and chosen for greatest relative intensity; § denotes extensive number of bands of similar intensity in the indicated wavelength range, with more

prominent heads identified in final column; r, v denotes degraded to red, violet; \* denotes forbidden line. Data taken from [9], with additional information on ozone from [10].

Mol.	System	Range/nm	Prominent bands/nm
C <sub>2</sub>	Swan system	436–668v	471.52 473.71 516.52 558.55 563.55
C <sub>2</sub>	high-pressure system	341–786v	468.02 589.93 644.23
C <sub>2</sub>	Spark system	339–410v	360.73 385.22 410.23
Cl <sub>2</sub>	conts absorption 250–400 nm	480–> 600r§	continua + bands
Cl <sub>2</sub> <sup>+</sup>		394–487r	454.91 461.36 468.26 475.10 479.47
CH	430 system <sup>a</sup>	430–489v	431.25 431.5 438.4
CH	390 system	387–403r	387.11 388.9
CH	314 system	314–316rv <sup>b</sup>	314.34 314.41 314.49 315.66
CH <sup>+</sup>		374–480r	374.37 395.44 422.53 <sup>c</sup>
CH <sub>2</sub>	comet head group	398–408	403.91 404.21 405.15
CN	cyanogen red	470–940r§	635.51 650.23 787.4 914.05 939.3
CN	cyanogen violet	358–460v	387.14 388.34 421.60
CO	Angstrom	412–662v	451.09 483.53 519.82 561.02
CO	Herzberg	368–571v	389.31 412.48 438.03
CO	fourth positive	201–279r§	204.63 206.76 208.99 219.68 222.15 246.32
CO <sup>+</sup>	first negative	200–315r	218.98 229.96 244.58 247.42 250.46 257.77
CO <sup>+</sup>	comet tail	308–640r	379.58 401.97 427.43 456.58
CO <sub>2</sub>	Duffenback & Barker	280–500r	313.29 324.69 337.00 350.32 366.16
CO <sub>2</sub>	288.3 & 289.6 narrow bands	287–289	288.18 288.40 289.75
H <sub>2</sub> O	infrared absorption	572–955	816.45 817.70 822.70 900.02 934.40 944.09
H <sub>2</sub> O	emission bands	568–967r	716.45 809.7 891.6 927.7 966.9
H <sub>2</sub> O <sub>2</sub>	continuous absorption	< 215–370	peak at 300
He <sub>2</sub>	complex structure of bands	320–640r	462.56 464.85 573.30v 639.87
N <sub>2</sub>	first positive	503–1042v§	580.43 646.85 654.48 891.16 1042
N <sub>2</sub>	second positive	281–498v	337.13 357.69 375.54 380.49
NH	strong peak		336.0 337.0
NH <sub>3</sub>	Schuster broad emission	500–600	563.5 567.0 maxima
NH <sub>3</sub>	UV absorption	< 230r	201.09 204.84 208.64 212.65 216.73
NO	β-system	201–527r§	289.26 304.30 320.69 338.64 358.35 380.09
O <sub>2</sub>	Hopfield emission	203–222v	203.08 207.66 212.31 217.00 221.75
O <sub>2</sub>	atmospheric absorption	538–551r	686.72* 759.37*
O <sub>3</sub>	Hartley broad absorption band	200–310	broad continuum, max at 255
O <sub>3</sub>	Huggins absorption	310–360	uv continuum + peaks, max 308
O <sub>3</sub>	Chappuis absorption	375–650	continuum + vibrational bands, max 602.5
OH	306.4 nm emission	244–402r	302.12 306.36 306.72 307.8 308.9
OH	visible <sup>d</sup>	370–580r	512.35 548.03

<sup>a</sup> Seen in emission in comet tails, but in absorption in solar spectrum.

<sup>b</sup> 314.34 is only v, and is most intense.

<sup>c</sup> Seen in absorption in stellar spectra.

<sup>d</sup> Can be detected in sunspots.



## 1.9 Characteristic Parameters for Typical Plasmas

### 1.9.1 Laboratory Plasma Reactors

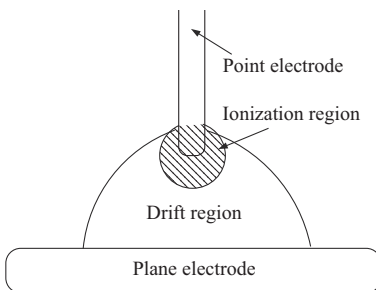
There is a wide variety of vessel and electrode geometry in laboratory devices; the following list is indicative, but not exhaustive. Table 1.16 gives typical operating parameters for various plasma devices.

#### 1.9.1.1 Corona Discharge

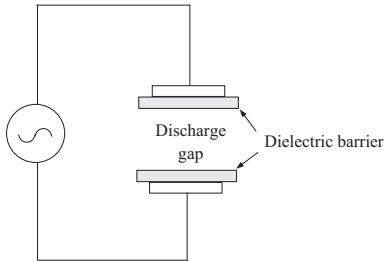
Also known as ‘point-to-plane’ discharge [11, 12], the ionizing electric field is produced by a marked asymmetry in the electrodes. The standard configuration, shown in Figure 1.2, is a sharply pointed electrode paired with a planar electrode, with the former producing a localized high electric field sufficient to ionize the neutral gas, and strike a plasma; a similar effect can be produced by electrodes in the form a wire inside a hollow cylinder. The ionization region is generally confined to a small area close to the high-field electrode, producing a drift region (between the ionization region and the flat electrode) in which charged particles (mainly electrons) react with neutrals and induce electron-moderated chemical reactions, including radical production. If the electric field is very high, plasma streamers can extend the ionizing region to encompass the second electrode. It is suitable for use over a wide range of pressures (including atmospheric), with applications that include ozone production, surface modification and combustion promotion.

#### 1.9.1.2 Dielectric Barrier Discharge

Also known as silent discharges, dielectric barrier discharges (DBD) [13] generally consist of a pair of AC-powered plane electrodes with at least one covered in a dielectric layer (Figure 1.3). The neutral gas breaks down in the usual manner, forming streamers. However, when the streamers bridge the gap between the elec-



**Figure 1.2** Typical configuration of a point-to-plane corona discharge, showing a plasma ionization region close to the high field at the point electrode, and the region of ion drift impinging on the flat electrode plate.



**Figure 1.3** Typical configuration of a dielectric barrier discharge (DBD), showing the powered electrodes and the dielectric layers; though two dielectric layers are shown, it is only necessary to have one dielectric layer present in the discharge gap.

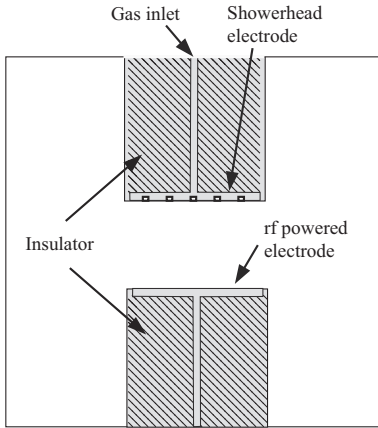
trodes, the dielectric layer allows free charge to accumulate which significantly affects the ongoing development of the discharge, including self-quenching. In particular, charge accumulated from one half-cycle of AC power is available to enhance the field in the subsequent half-cycle.

#### 1.9.1.3 GEC Reference Cell

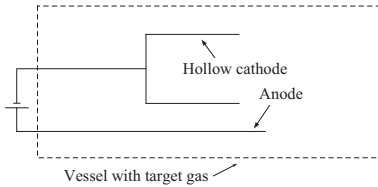
A standard parallel plate, capacitively-coupled rf plasma reactor designed for researching plasma discharge phenomena of direct relevance to the plasma technology sectors [14]. By designing a standard reactor for general use in different plasma conditions, the effects of reactor geometry could be minimized. Figure 1.4 shows a simplified schematic of a typical arrangement; in fact, either electrode can be powered independently, and the electrode spacing can be adjusted. Not shown on the schematic are the 8 diagnostic ports in the midplane. The showerhead electrode has 169 equally spaced holes placed in concentric circles for smooth gas feeding; the reactor is designed to work at a base pressure close to  $10^{-5}$  Pa. Gas flow rates in the range 2–25 sccm (standard cubic centimeters per second) can be accommodated. At 10 sccm, the reactor pressure is generally not below 8 Pa.

#### 1.9.1.4 Hollow Cathode Discharge

Hollow cathode devices (HCDs) [15–17] have the cathode in the form of a cup or cylinder, closed at one end, with the anode near the open end of the cathode (Figure 1.5). This arrangement allows the HCD to operate in the transition between the glow-discharge and a low-pressure arc discharge, supporting high current density negative glow (electron current) enclosed within the cathode structure. Because of their greater efficiency compared to a conventional plane-parallel electrode arrangement, HCD are used in spectral analyses of gas samples, and are valuable as photon sources (lamps). Microhollow cathode discharges (MHCDs) are similar in concept to HCD but are very much smaller, having scale lengths in the 10 s of mm. MHCD are often referred to as microdischarges, though the latter term additionally refers to devices which are similar in topology to HCD, but operate at atmospheric pressures and using AC power.



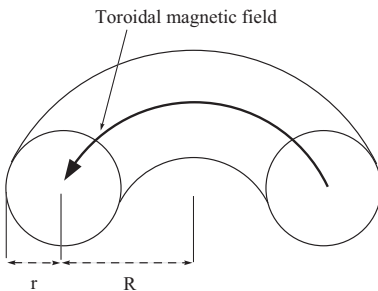
**Figure 1.4** Simplified schematic of a Gaseous Electronics Conference (GEC) Reference Cell, showing the showerhead upper electrode and powered lower.



**Figure 1.5** Simplified schematic of a typical hollow cathode discharge arrangement.

### 1.9.1.5 Tokamak

The primary device for magnetic confinement fusion, the tokamak holds deuterium–tritium plasma in a toroidal chamber, shown schematically in Figure 1.6. The strong toroidal magnetic field (shown in bold arrow) is imposed by external field coils (not shown), and combines with the poloidal self-field of the plasma; the resultant helical magnetic field structure inhibits the plasma from touching the vacuum vessel. The toroidal (or major) radius  $R$  and poloidal (or minor) radius  $r$  are key



**Figure 1.6** Schematic of a tokamak reactor, showing the major  $R$  and minor  $r$  radii for a circular cross-section vessel.

**Table 1.15** Selected critical data for various tokamaks. § denotes spherical tokamak.

Tokamak	Major radius/m	Minor radius/m	Peak B (/T)	Peak current/MA	Heating/MW
Alcator C-Mod	0.67	0.22	2	8	9.5
Asdex upgrade	1.65	0.5–0.8	3.1	1.6	27
COMPASS	0.56	0.23–0.38	2.1	0.4	1
DIII-D	1.66	0.67	2.2	3	31
ITER	6.2	2.0	5	15	110
JET	2.96	1.25–2.1	3.45	5	51
JT-60	3.4	1.0	4	3	55
KSTAR	1.8	0.5	3.5 <sup>a</sup>	2.0	28
MAST§	1.5	–	0.84	2.0	7.5

<sup>a</sup> Superconducting coils.

**Table 1.16** The operating parameters for rf parallel plate plasma etching, and high-density plasma reactor [18].

Quantity	RF	High-Density
Pressure/Pa	10 <sup>-1</sup> –10 <sup>3</sup>	10 <sup>-2</sup> –10
Pressure/Torr	0.001–10	10 <sup>-4</sup> –10 <sup>-1</sup>
Power/W	50–10 <sup>3</sup>	10 <sup>2</sup> –5 × 10 <sup>3</sup>
Frequency/MHz	0.1–100	0.1–20 or 2.45 GHz
Gas flow rate/sccm <sup>a</sup>	10–3 × 10 <sup>3</sup>	10–200
T <sub>e</sub> /eV	1–10	1–10
Plasma density/m <sup>-3</sup>	10 <sup>14</sup> –10 <sup>17</sup>	10 <sup>16</sup> –10 <sup>19</sup>
Fractional ionization	10 <sup>-7</sup> –10 <sup>-4</sup>	10 <sup>-4</sup> –10 <sup>-1</sup>
Ion bombarding energy/eV	50–10 <sup>3</sup>	10–500
Ion bombarding flux/ mA cm <sup>-2</sup>	10 <sup>-2</sup> –5	1–50
Magnetic field/T	0	0–0.1

<sup>a</sup> Standard cubic centimeters per second.

parameters in determining the reactor geometry. The main fusion reaction is as follows:



where the neutron has 14.1 MeV energy. Deuterium is a naturally occurring isotope of hydrogen; tritium has a short half-life of 12.3 years, and so has negligible natural abundance. Instead, it can be bred from lithium via the following reactions:

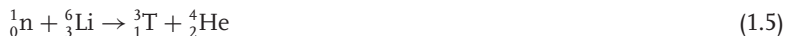


Table 1.15 gives characteristic data for a range of tokamaks. Spherical tokamaks are devices in which the major radius is reduced to a minimum, as they are essen-

tially spheres with a central column dividing the chamber, making them formally toroidal in topological form.

### 1.9.2

#### Terrestrial and Solar Plasmas

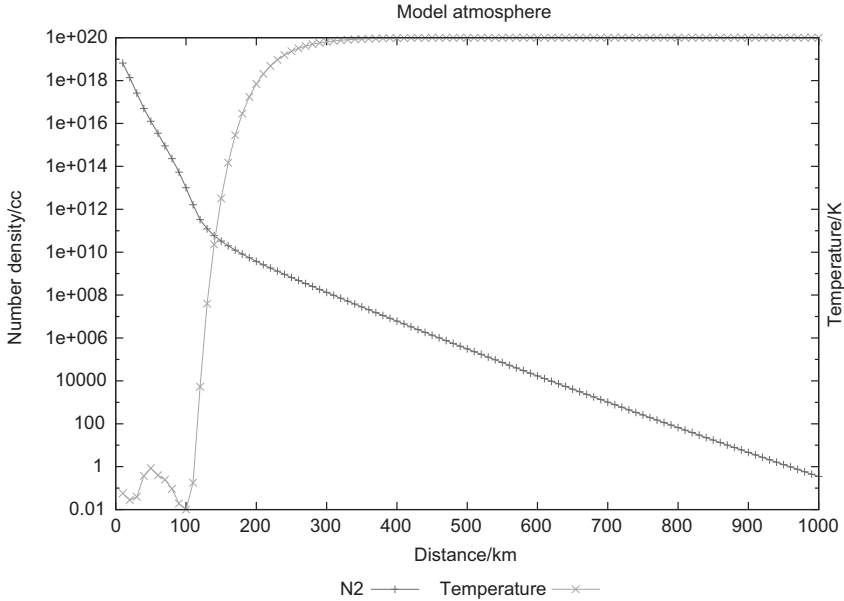
The data in this section characterizes the distribution of neutral and ionized species throughout the atmospheres of the earth and the sun.

**Table 1.17** Ionospheric parameters [19].

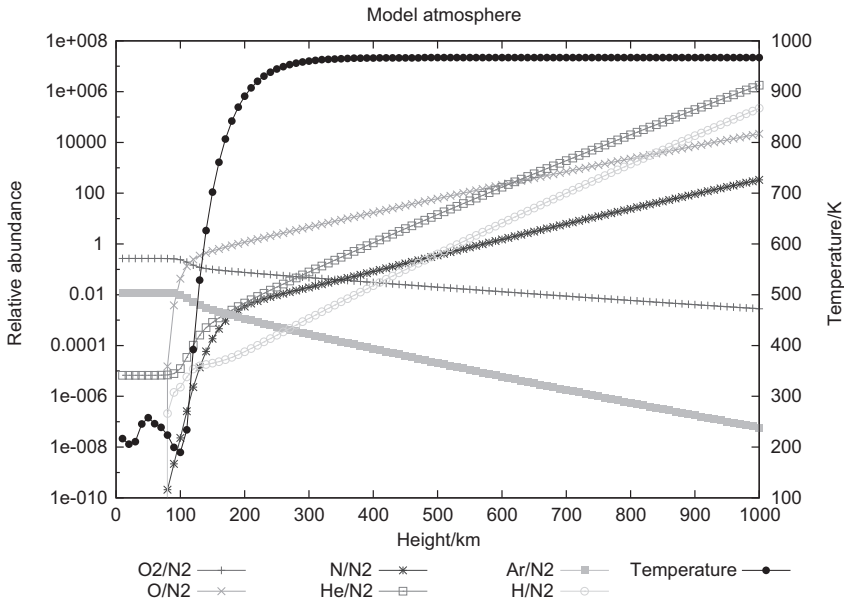
Ionospheric region	Height/km	$n_e/m^{-3}$ (day)	$n_e/m^{-3}$ (night)
D	50–90	$10^9$	$10^8$
E	90–140	$10^{11}$	$< 10^{10}$
F <sub>1</sub>	140–200	$3 \times 10^{11}$	$10^{10}$
F <sub>2</sub>	200–400	$10^{12}$	$10^{11}$

**Table 1.18** Solar plasma parameters [20, 21].

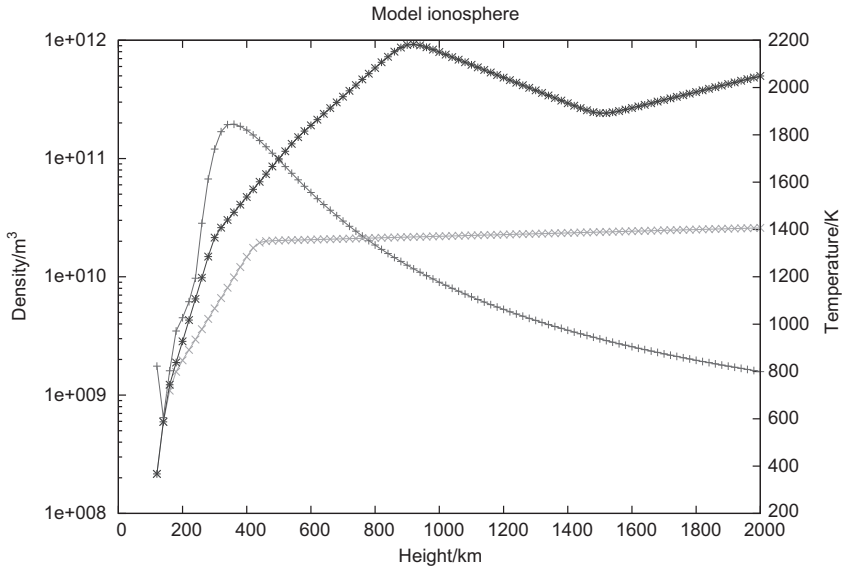
Quantity	Region	Typical value
Total number density/ $m^{-3}$	photosphere	$10^{22}$ – $10^{23}$
Electron number density/ $m^{-3}$	photosphere	$10^{18}$ – $10^{20}$
Total number density/ $m^{-3}$	chromosphere	$10^{16}$ – $10^{22}$
Electron number density/ $m^{-3}$	chromosphere	$10^{16}$ – $10^{18}$
Total number density/ $m^{-3}$	corona	$10^8$ – $10^{15}$
Electron number density/ $m^{-3}$	corona	$10^8$ – $10^{15}$
Temperature/K	photosphere	$4 \times 10^3$ – $6 \times 10^3$
Temperature/K	chromosphere	$\sim 3 \times 10^3$ – $10^4$
Temperature/K	corona	$> 10^6$
Magnetic field strength/T	poles	$\sim 10^{-4}$
Magnetic field strength/T	sunspot	$\sim 0.3$
Magnetic field strength/T	prominence	$10^{-3}$ – $10^{-2}$
Magnetic field strength/T	chromospheric plage	$\sim 10^{-2}$



**Figure 1.7** Model atmosphere MSIS E 90 from the Virtual Ionosphere, Thermosphere, Mesosphere Observatory (VITMO). The curves show the Nitrogen molecule number density (left-hand axis) and temperature (right-hand axis) as a function of height above sea level.

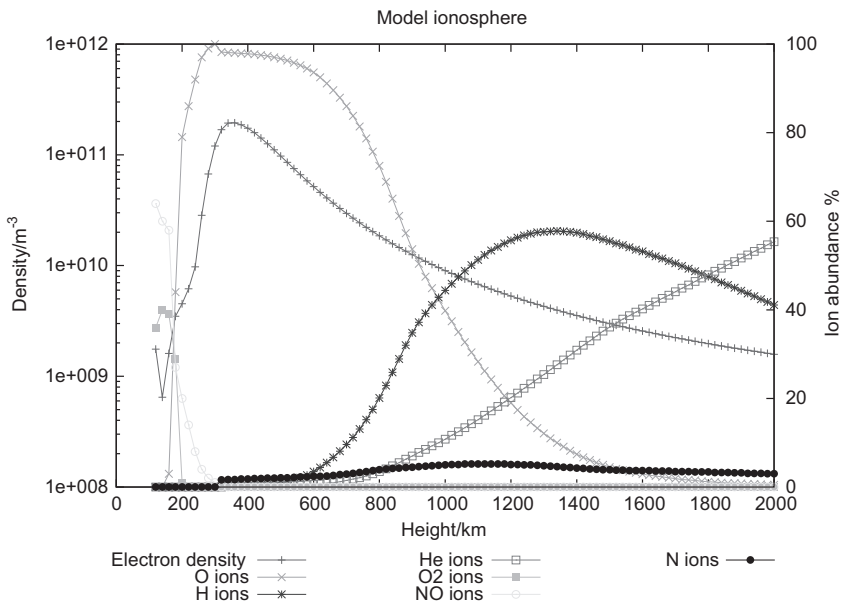


**Figure 1.8** Model atmosphere as for Figure 1.7. The curves show the relative abundance by number of various chemical species (left-hand axis) and temperature (right-hand axis) as a function of height above sea level.



**Figure 1.9** Model Ionosphere based on International Reference Ionosphere IRI 2007, for which the heights of the various regions are as follows: D: 88 km; E: 110 km; and F<sub>2</sub>: 350 km.

Plots shown are electron density (left-hand vertical axis), electron and ion temperatures (right-hand vertical axis) as functions of height.



**Figure 1.10** Model Ionosphere based on International Reference Ionosphere IRI 2007, for which D region height is 88 km, E 110 km, F<sub>2</sub> 350 km. Plots shown are electron density (left-hand vertical axis), and relative ion abundance (right-hand vertical axis) as functions of height.

