

# Appendix 1

## System of Units Used in the Book

---

*Units of physical properties measurements*, based on the International System of units (SI) are described below. According to this system the basic units in mechanics are: meter (m), second (sec), kilogram (kg); an additional unit is the radian—a unit of measurement of a flat angle (rad) and that of a solid angle steradian (sr). All other units of the SI system are derived and can be obtained with the help of corresponding transformations:

Area unit—square meter (area of a square with a 1 m side)

$$[S] = 1 \text{ m}^2.$$

–Volume unit—cubic meter (volume of a cube with a 1 m side)

$$[V] = 1 \text{ m}^3.$$

–Velocity unit—meter per second (velocity of uniform straight line motion; 1 m per 1 sec)

$$[v] = 1 \text{ m/sec}.$$

–Acceleration unit—meter per square second (acceleration when the uniform straight line motion velocity change is 1 m/sec)

$$[a] = 1 \text{ m/sec}^2.$$

–Frequency unit—second to the power of minus one (at revolution) and hertz (Hz) (unit of oscillation frequency; the frequency when a single periodic process is accomplished in 1 sec)

$$[\nu] = 1 \text{ sec}^{-1}.$$

–Angular velocity unit—1 radian per second (angular velocity when a uniform rotating body turns by 1 rad in 1 sec)

$$[\omega] = 1 \text{ rad/sec.}$$

–Angular acceleration unit—1 radian per 1 sec in the second power (angular acceleration when angular velocity changes by 1 rad/sec in 1 sec)

$$[\varepsilon] = 1 \text{ rad/sec}^2.$$

–Force unit—newton (N) (the amount of force required to give a 1 kg mass body an acceleration of 1 m/sec<sup>2</sup>)

$$[F] = 1 \text{ N} = 1 \text{ kg m/sec}^2.$$

–Density unit—kilogram per cubic meter (the density of a uniform substance whose mass per 1 m<sup>3</sup> is equal to 1 kg)

$$[\rho] = 1 \text{ kg/m}^3.$$

–Pressure unit—pascal (Pa) (pressure produced by a force of 1 N acting on an area of 1 m<sup>2</sup>)

$$[P] = 1 \text{ Pa} = 1 \text{ N/m}^2.$$

–Momentum unit—kg m/sec (a body of mass 1 kg moving translational with a velocity of 1 m/sec)

$$[p] = 1 \text{ kg m/sec.}$$

–Force impulse—newton × second (a force impulse produced by a force of 1 N for 1 sec)

$$[F \cdot t] = 1 \text{ N sec.}$$

–Work (energy) unit—joule (J) (the amount of work done when an applied force of 1 N moves in the direction of the force through a distance of 1 m)

$$[A] = 1 \text{ J} = 1 \text{ Nm.}$$

–Power unit—watt (W) (a watt is used to measure power or the rate of doing work; 1 W is a power of 1 J per second).

$$[W] = 1 \text{ W(J/sec).}$$

–Torque unit—newton  $\times$  meter (moment of force produced by a force of 1 N relative to a point which is at distance of 1 m away from the force action line)

$$[M] = 1 \text{ N m.}$$

–Moment of inertia unit—kilogram  $\times$  square meter (moment of inertia of a material point 1 kg in mass relative to a rotation axis 1 m away)

$$[I] = 1 \text{ kg m}^2.$$

–Angular momentum unit—kilogram  $\times$  square meter per second (angular momentum of a body with a moment of inertia in 1 kg  $\text{m}^2$  rotated with angular velocity 1 rad/sec)

$$[L] = 1 \text{ kg m}^2/\text{sec.}$$

*In addition to the units presented above in molecular physics following units are also used.*

Unit of heat energy or heat—calorie; 1 cal = 4.1868 J

$$[Q] = 1 \text{ cal.}$$

Heat capacity unit—calorie per kelvin (amount of heat to warm a body by 1 K)

$$[C] = 1 \text{ cal/K.}$$

–Specific heat capacity unit—calorie per kilogram  $\times$  kelvin (amount of heat to warm 1 kg of a substance by 1 K)

$$[C_{\text{sp}}] = 1 \text{ cal/kg K.}$$

Mole heat capacity unit—calorie per mole  $\times$  kelvin (amount of heat to warm one mole of substance by 1 K)

$$[C_{\text{mole}}] = 1 \text{ cal/mole K.}$$

In addition to the mechanical units of measurements, *in the sections describing electricity and magnetism*, one basic unit—the ampere (A) and a number of derivative units are used. In the SI system 1 A is defined as the force of that current which produces a specific force between two parallel infinitely long conductors which are 1 m apart, in  $2 \times 10^{-7}$  H/m.

Charge unit—coulomb (C) (the charge that runs through a cross-section of a conductor when a current of 1 ampere is flowing)

$$[q] = 1 \text{ A} \times 1 \text{ sec (Asec)}$$

(then an electric current  $I$  in 1 A corresponds to 1 coulomb transfer in 1 sec)

$$[I] = \frac{1 \text{ C}}{1 \text{ sec}} \quad (\text{A}).$$

—Current density unit—ampere per square meter (electric current of 1 A per 1 m<sup>2</sup> of cross-section of a conductor)

$$[j] = \frac{1 \text{ A}}{1 \text{ m}^2} \quad (\text{A/m}^2).$$

—Electric field strength unit—volt/meter (electric field strength, acting on a point charge 1 C with a force 1 N)

$$[E] = \frac{1 \text{ N}}{1 \text{ C}} = \frac{1 \text{ V}}{1 \text{ m}} \quad (\text{kg m/A sec}^3).$$

—Electric displacement (induction) unit—coulomb/meter<sup>2</sup> (electric field strength multiplied by  $\epsilon\epsilon_0$ )

$$[D] = \epsilon\epsilon_0 E (\text{A sec/m}^2).$$

—Electric field potential unit—volt (V) (electric field potential in which the charge of 1 C possesses potential energy 1 J)

$$[\varphi] = 1 \text{ J/1 C} \quad (\text{kg m}^2/\text{A sec}^3).$$

—Electric dipole moment unit—coulomb  $\times$  meter (dipole electric moment of a pair of opposite charges equal in value and being 1 m apart)

$$[p] = 1 \text{ C} \times 1 \text{ m} (\text{A sec m}).$$

—Electric quadrupole moment—coulomb  $\times$  meter<sup>2</sup> (quadrupole electric moment of a system of two pairs of opposite charge equal in value of 1 C displaced alternately in square corners at side length 1 m)

$$[Q] = 1 \text{ C} \times 1 \text{ m}^2 (\text{A sec m}^2).$$

Electric linear density unit—coulomb/meter (charge of 1 C uniformly distributed along a line of 1 m)

$$[\tau] = 1 \text{ C}/1 \text{ m (A sec/m)}.$$

Electric surface charge density unit—coulomb/meter<sup>2</sup> (charge of 1 C, uniformly distributed over an area of 1 m<sup>2</sup>)

$$[\sigma] = \frac{1 \text{ C}}{1 \text{ m}^2} \text{ (A sec/m}^2\text{)}.$$

Electric volume charge density unit—coulomb/meter<sup>3</sup> (charge, uniformly distributed in a volume of 1 m<sup>3</sup>)

$$[\rho] = \frac{1 \text{ C}}{1 \text{ m}^3} \text{ (A sec/m}^3\text{)}.$$

—Dielectric polarization unit—coulomb/meter<sup>2</sup> (a dielectric's volumetric dipole moment)

$$[\mathfrak{P}] = \frac{1 \text{ C}}{1 \text{ m}^2} \text{ (A sec/m}^2\text{)}.$$

Dielectric susceptibility unit—dimensionless (polarization of isotropic dielectric in a unit field strength divided by  $\epsilon_0$ )

$$[\chi].$$

Dielectric permeability unit—dimensionless (a value indicating by how much an averaged macroscopic field in a dielectric is less than an external field)

$$[\epsilon] = \frac{E_0}{E}.$$

Polarization of a molecule unit—meter<sup>3</sup> (a molecular dipole moment in a field of a unit strength divided by  $\epsilon_0$ )

$$[\alpha] = \frac{P}{\epsilon_0 \times E} \text{ (m}^3\text{)}.$$

Electronic capacitance unit—farad (F) (capacitance of conductor, which is charged to potential 1 V receiving a charge of 1 C)

$$[C] = \frac{1 \text{ C}}{1 \text{ V}} \text{ (A}^2 \text{ sec}^4\text{/(kg m}^2\text{))};$$

–Magnetic moment unit—ampere  $\times$  meter<sup>2</sup> (electric current of 1 A flowing around an area of 1 m<sup>2</sup>)

$$[\mathcal{M}] = 1 \text{ A} \times 1 \text{ m}^2 (\text{A m}^2).$$

–Off-system unit—Bohr magneton  $\mu_B$  ( $1 \mu_B = 0.927 \times 10^{-23} \text{ A m}^2$ ).

Magnetic field induction unit—tesla (T) (maximal magnetic force moment, acting on a unit magnetic moment)

$$[B] = \frac{1 \text{ N}}{1 \text{ A m}^2} \quad (\text{kg}/(\text{A sec}^2)).$$

Strength of magnetic field unit—ampere/meter (magnetic field induction, divided by  $\mu_0\mu$ )

$$[H] = \frac{1 \text{ A}}{\text{m}} \quad (\text{A/m}).$$

Magnetization unit—ampere/meter (moment of an unit volume moment)

$$[\mathfrak{M}] = \frac{1 \text{ A}}{1 \text{ m}} = (\text{A/m}).$$

Magnetic susceptibility unit—dimensionless (magnetization of an unit volume of a magnetic in an unit strength field)

$$[\chi].$$

–Specific magnetic susceptibility unit—meter<sup>3</sup>/kilogram (magnetization of a unit mass of a magnetic in a field of unit strength)

$$[\chi_{sp}] = \frac{\chi}{\rho} \quad (\text{m}^3/\text{kg}).$$

Mole magnetic susceptibility unit—meter<sup>3</sup>/mole (magnetization of one mole of magnetics in a field of unit strength)

$$[\chi_M] = \frac{M \times \chi}{\rho} \quad (\text{m}^3/\text{mole}).$$

Magnetic permeability unit—dimensionless (shows how many times greater is the magnetic field than an external magnetic field)

$$[\mu] = \frac{B}{B_0}.$$

Magnetic flux unit—weber (Wb) (a magnetic field induction flux in 1 T through the surface of unit area)

$$[\Phi] = 1 \text{ T} \times 1 \text{ m}^2 = 1 \text{ Wb}; \quad (\text{kg m}^2/(\text{A sec}^2)).$$

Inductance unit—henry (H) (inductance of a conductor in which at a current of 1 A appears a total magnetic leakage of 1 Wb)

$$[L] = 1 \text{ Wb}/1 \text{ A}; \quad (\text{kg m}^2/(\text{A}^2 \text{ sec}^2)).$$

Some important physical constants:

---

Acceleration of free falling	$g = 9.81 \text{ m/sec}^2$
Gravitational constant	$G = 6.67 \times 10^{-11} \text{ m}^3/(\text{kg}/\text{sec}^2)$
Avogadro constant	$N_A = 6.02 \times 10^{23} \text{ mol}^{-1}$
Mole gas constant	$R = 8.31 \text{ J}/(\text{K mol})$
Molar volume at normal conditions	$V_m = 22.4 \times 10^{-3} \text{ m}^3/\text{mol}$
Boltzmann constant	$\kappa = 1.38 \times 10^{23} \text{ J/K}$
Elementar charge	$ e  = 1.60 \times 10^{19} \text{ C}$
Electron mass	$m_e = 9.11 \times 10^{-31} \text{ kg}$
Specific electron charge	$(e/m) = 1.76 \times 10^{11} \text{ C/kg}$
Light velocity in vacuum	$c = 3.00 \times 10^8 \text{ m/sec}$
Stefan–Boltzmann constant	$\sigma = 5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$
Win shift constant	$C = 2.90 \times 10^{-3} \text{ m K}$
Planck's constant	$h = 6.63 \times 10^{-34} \text{ J sec}; \hbar = h/2\pi = 1.05 \times 10^{-34} \text{ J sec}$
Rydberg constant	$R = 1.097 \times 10^7 \text{ m}^{-1}$
First Bohr orbit radius	$a = 5.29 \times 10^{-11} \text{ m}$
Compton wavelength	$\lambda_C = 2.43 \times 10^{-12} \text{ m}$
Bohr magneton	$\mu_B = 9.27 \times 10^{-24} \text{ J/T}$
Ionization energy of hydrogen atom	$E_i = 2.16 \times 10^{-18}; J = 13.56 \text{ eV}$
Atomic unit of mass	$1 \text{ a.u.m} = 1.66 \times 10^{-27} \text{ kg}$
Nuclear magneton	$\mu_N = 5.05 \times 10^{-27} \text{ J/T}$
Electric constant	$\epsilon_0 = 0.885 \times 10^{-11} \text{ F/m}$
Magnetic constant	$\mu_0 = 1.26 \times 10^{-6} \text{ H/m}$

---

This page intentionally left blank



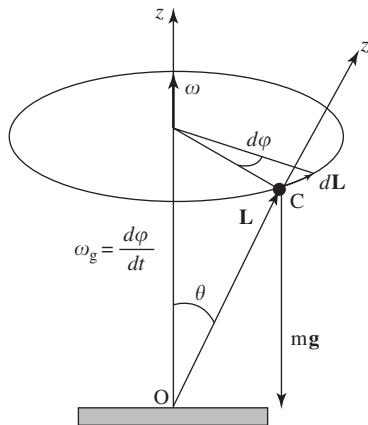
# Appendix 2

## Gyroscope Precession in a Gravity Field

---

A symmetric body with a single motionless point and able to rotate at high angular velocity  $\omega$  around an axis  $z'$  passing through this motionless point is called a gyroscope. There are two types: balanced (the motionless point coincides with the center of inertia) and unbalanced (where this condition is not fulfilled). A child's spinning top is a primitive example of an unbalanced gyroscope.

Figure A2.1 shows an unbalanced gyroscope acquiring a rotation (precession) in a gravitational field. The pivot point  $O$  is a unique motionless point and the axis of rotation  $z'$  passes through it. The gravity force is directed vertically downwards along axis  $z$ . The angle between axes  $z$  and  $z'$  is denoted by  $\theta$  and is assumed to be small. In the figure, for simplicity, the angular momentum vector  $\mathbf{L}$  terminates in the center of mass  $C$ , the distance  $OC$  being  $l_C$ . According to the basic equation of rotational motion dynamics, we can write  $d\mathbf{L} = M d\boldsymbol{\phi}$  (refer to (1.3.57)). The force momentum (torque) of the gravitational force relative to point  $C$  is  $M = mgl_C \sin\theta$ .



The rotation of the gyroscope's axis  $z'$  relative to the vertical axis  $z$  is referred to as gyroscope precession. Under the action of the gravity force momentum the vector of the angular momentum  $\mathbf{L}$  of the unbalanced gyroscope obtains an increment  $d\mathbf{L}$  directed along

the vector  $\mathbf{M}$  (see (1.3.57) and Figure 1.19). Since  $d\mathbf{L}$  is perpendicular to  $\mathbf{L}$  the modulus of  $\mathbf{L}$  is constant and only precession takes place. The gyroscope precession angular velocity  $\omega_g$ , as seen in Figure A 2.1, can be found as

$$\omega_g = \frac{d\varphi}{dt} = \frac{mg\ell_C \sin\theta}{I\omega_z \sin\theta} = \frac{mg\ell_C}{I\omega_z}. \quad (\text{A2.1})$$

Note that the angle  $\theta$  is small and  $I$  and  $\omega$  regarding both axes,  $z$  and  $z'$ , are approximately same. It can be seen that the precession angular velocity  $\omega_g$  is higher, the lower the gyroscope's moment of inertia  $I$  and angular velocity  $\omega_z$ ;  $\omega_g$  does not depend on the angle  $\theta$  between axis  $z$  and  $z'$ .

Anyone can conduct an experiment using a child's spinning top.

# Appendix 3

## An Electrostatic Field of an Arbitrary Distributed Charge

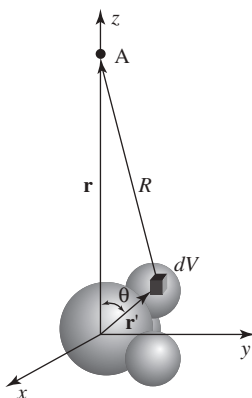
---

Among the real problems the chemist can come across in practice, a simple situation with a discrete set of point charges is rarely seen. Any molecule consists of positively charged nuclei encircled by negative electrons, each particle being vibrated around positions of equilibrium. Therefore, the overall charge distribution is described in this case by the distribution function  $\rho(r)$ :

$$dq = \rho(\mathbf{r})dV. \quad (\text{A3.1})$$

The charge density distribution  $\rho(\mathbf{r})$  is of great importance because it permits the calculation of a wide number of molecular and crystal properties and enable us to follow the paths of chemical reactions.

Consider a field created by the electric charge system described by the function  $\rho(\mathbf{r})$  (refer to Figure A3.1). Our task is to calculate the electrostatic field created by this system in a certain point A. Direct an axis  $z$  of the Cartesian coordinate system in such a way that



it crosses point A. The electrostatic potential in point A is the superposition of contributions from all elements  $dq$ .

$$\varphi(r) = \int_V \frac{\rho(r')dV'}{R} = \int_V \frac{\rho(r')dV'}{|r-r'|}, \quad (\text{A3.2})$$

where  $r$  is the  $z$  component of the radius-vector of point A,  $r'$  is the argument of the function  $\rho(r')$ ,  $|\mathbf{R}| = |\mathbf{r}-\mathbf{r}'|$  is the distance from the element  $dV$  to point A. The integration is over the coordinate  $\mathbf{r}'$  over the whole charge containing space. Denoting the angle between vectors  $\mathbf{r}$  and  $\mathbf{r}'$  as  $\theta$  and using the cosine theorem; we obtain  $R = (r^2 + r'^2 - 2rr' \cos\theta)^{1/2}$ . Then the integral can be rewritten as  $\varphi_A = \int \rho(r')dV' (r^2 + r'^2 - 2rr' \cos\theta)^{-1/2}$ . If we calculate the field far from the origin (i.e.,  $r' \ll r$ ) the expression

$$\frac{1}{R} = \frac{1}{(r^2 + r'^2 - 2rr' \cos\theta)^{1/2}} = \frac{1}{r} \left[ 1 + \left( \frac{r'^2}{r^2} - 2\frac{r'}{r} \cos\theta \right) \right]^{-1/2}$$

can be decomposed into a series and can be expanded over the  $r'$  orders

$$(1 + \beta)^{-1/2} = 1 - \frac{1}{2}\beta + \frac{3}{8}\beta^2 + \dots,$$

where

$$\beta = \left[ \left( \frac{r'}{r} \right)^2 - 2\frac{r'}{r} \cos\theta \right].$$

Summing up all the terms with the same order of  $r'/r$  and neglecting the terms of higher orders than quadratic, we obtain the expression

$$\frac{1}{R} = \frac{1}{r} \left[ 1 + \frac{r'}{r} \cos\theta + \left( \frac{r'}{r} \right)^2 \times \frac{1}{2} (3 \cos^2\theta - 1) \right].$$

Introducing this expression into eq. (A3.2) and taking into account that integration is accomplished over  $r'$ , we can obtain for  $\varphi_A$  the sum

$$\begin{aligned} \varphi_A &= \frac{1}{r} \int \rho(r')dV' + \frac{1}{r^2} \int r' \cos\theta \rho(r')dV' \\ &+ \frac{1}{r^3} \int r'^2 \times \frac{1}{2} (3 \cos^2\theta - 1) dV'. \end{aligned} \quad (\text{A3.3})$$

The magnitude of each of these integrals depends only on the properties of the electron density function  $\rho(\mathbf{r}')$ . Being calculated for the given system they can be expressed as numbers  $k_0$ ,  $k_1$  and  $k_2$  correspondingly. The dependence of  $\varphi_A$  on  $|\mathbf{r}'|$  will be expressed by the sum

$$\varphi_A = \frac{k_0}{r} + \frac{k_1}{r^2} + \frac{k_2}{r^3}. \quad (\text{A3.4})$$

The  $k_n$  are referred to as the electric moments of the system.

Let us analyze each term of this sum. The  $k_0$  value is expressed by an integral

$$k_0 = \int \rho(r') dV'. \quad (\text{A3.5})$$

and is the total charge of the system concentrated in origin. It is referred to as a monopole moment or simply a monopole. For a neutral system  $k_0 = 0$ .

The coefficients  $k_1$  and  $k_2$ , unlike  $k_0$ , depend on charge distribution. The coefficient  $k_1$  characterizes an electric dipole moment

$$k_1 = \int r' \cos \theta \rho(r') dV'. \quad (\text{A3.6})$$

Since the value  $r' \cos \theta$  is  $z$ -coordinate of element  $dV'$ , this term characterizes the relative displacements of the positive and negative charges  $\rho(r') dV'$  along this axis. Indeed, if one imagines a system consisting of two dissimilar charges  $q$  in points  $(0,0,z)$  and  $(0,0,-z)$  with  $z = 1/(2l)$ , then a value  $r' \cos \theta = \pm (1/2)\ell$  can be factorized from the integral. The resultant expression  $\int \rho(r') dV'$  will be equal to  $q$  and the whole coefficient  $k_1$ , which is now equal to  $lq = p$ , composes the electric dipole moment oriented along the  $z$ -axis (see Section 4.1.5 and eq. (4.1.29)).

The coefficient  $k_2$

$$k_2 = \int r'^2 \rho(r') \frac{1}{2} (3 \cos^2 \theta - 1) dV'. \quad (\text{A3.7})$$

is a so-called *quadrupole moment*. Try to understand what electron density distribution is described by such a factor. For spherically symmetric electron distribution  $k_2 = 0$ . It follows from a specific type of  $k_2$  factor: keeping in mind that  $r'^2 = x^2 + y^2 + z^2$  for the specified symmetry all three coordinates are equivalent, therefore  $x^2 + y^2 + z^2 = 3z^2$  and, consequently,  $3z^2 - r'^2 = 0$ . A flattened out electron density model is the charge  $q$  rotating around an  $z$ -axis at a level  $z = 0$  at a distance  $r_0$  from the axis. Then  $\theta = \pi/2$  and the expression in brackets becomes negative. Since  $r = \text{const.}$ , then  $k_2$  is equal to  $-r_0^2 q$  for a positive charge and  $+r_0^2 q$  for a negative charge. It is reasonable to assume that as for

every “flattened out” distribution the quadrupole moment has such signs. It is easy to show that for the “extended” model distribution the signs will be the opposite.

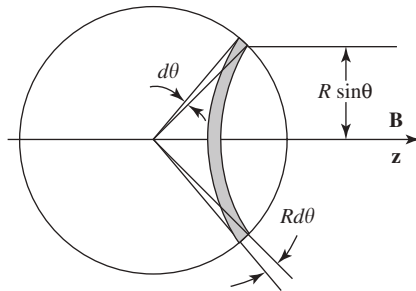
Expression (A3.4) shows that in the electrostatic field created by a particular system, the electric potential falls differently with distance (refer to Table 8.1) the higher the order of the moment, the sharper the potential falling down. Even neutral systems (atoms, molecules) create an electric field by means of which these systems interact with each other. Accordingly, the higher the order of the moment, the lower the energy of interaction; for example, dipole–dipole interaction is appreciably weaker than the interaction of monopoles (Coulomb interaction). All this information is useful in Chapter 8.

# Appendix 4

## Langevin Theorem

---

Consider a system consisting of identical molecules weakly interacting with each other, characterized by a magnetic dipole moment  $\mathcal{M}$ . An external magnetic field  $\mathbf{B}$  acts on the system trying to orient all magnetic moments along  $z$  axis contrary to chaotic thermal motion. Allocate in this system a spherical volume  $V$  of a radius  $R$ . Suppose that there are a large enough number of molecules in this volume with all possible orientations of magnetic moments. Among all  $N$  molecules in the volume  $V$  we shall denote as  $dN(\theta)$  such molecules whose magnetic moments form an angle from  $\theta$  up to  $\theta + d\theta$  with a direction of vector  $\mathbf{B}$  (Figure A4.1).



These  $dN(\theta)$  molecules account for a physically infinitesimal elementary volume  $dV(\theta)$ . Then the concentration of such molecules is

$$n_\theta = \frac{dN}{dV}. \quad (\text{A4.1})$$

An equilibrium distribution of noninteracting particles in an internal force field is described by the Boltzmann formula  $n = C \exp(-U/\kappa T)$ , where  $C$  is a normalizing coefficient. Since the potential energy of the dipoles in the external field is determined by a ratio (eq. (5.1.31)) ( $U = -\mathcal{M}B \cos\theta$ ), the equilibrium distribution of dipoles upon potential energies (i.e., on various orientations of the magnetic moments) in field  $B$  can be written as:

$$n_\theta = C \exp\left(\frac{\mathcal{M}B}{\kappa T} \cos\theta\right). \quad (\text{A4.2})$$

From the last two equations we can derive

$$dN(\theta) = C \exp\left(\frac{\mathcal{M}B}{\kappa T} \cos\theta\right) dV(\theta). \quad (\text{A4.3})$$

Express an elementary volume  $dV(\theta)$ , occupied by a molecule the magnetic moment of which is directed at an angle  $\theta$ , through the angles  $\theta$  and  $d\theta$ . Since  $dV(\theta) = (V/4\pi)d\Omega$ , where  $d\Omega$  is an elementary solid angle obtained by two coaxial cones with a common vertex at point 0 and openings of  $2\theta$  and  $2\theta + d\theta$ , then from the solid angle definition (4.1.10) and Figure A4.1, it follows that

$$d\Omega = \frac{dS}{R^2} = \frac{2\pi(R \sin\theta)(R d\theta)}{R^2} = 2\pi \sin\theta d\theta.$$

Then  $dV(\theta) = (1/2) V \sin\theta d\theta$  and (A4.3) could be rewritten as

$$dN = \frac{1}{2} CV \exp\left(\frac{\mathcal{M}B}{\kappa T} \cos\theta\right) \sin\theta d\theta. \quad (\text{A4.4})$$

The constant  $C$  can be determined from the normalizing procedure: the integral from  $dN(\theta)$  over all possible orientation of  $\theta$  angles (from 0 to  $\pi$ ) must equal the total number of molecules  $N$  in volume  $V$ , that is:

$$\int_0^\pi dN(\theta) = N. \quad (\text{A4.5})$$

To simplify further calculations mark  $(\mathcal{M}B/\kappa T)$  as  $a$  and  $\cos\theta$  as  $x$ ; then  $\sin\theta d\theta = -dx$ . This change brings about the change in limits in (A4.5): instead of the inferior limit there will be 1 ( $\cos\theta = 1$ ), and the superior limit will be  $-1$  ( $\cos\pi = -1$ ). After such transformation and change of a sign before an integral one arrives at

$$\frac{1}{2} CV \int_{-1}^1 e^{ax} dx = N.$$

After these transformations we obtain

$$\frac{1}{2} CV \frac{e^a - e^{-a}}{a} = N,$$



hence

$$C = \frac{2aN}{(e^a - e^{-a})V} \quad \text{or} \quad C = \frac{2a}{(e^a - e^{-a})}n,$$

where  $n = N/V$  is the total molecules concentration. Then  $dN(\theta)$  can be rewritten as

$$dN(\theta) = \frac{a}{e^a - e^{-a}} n V e^{a \cos \theta} \sin \theta d\theta. \quad (\text{A4.6})$$

These  $dN(\theta)$  dipoles make a contribution of  $d\mathfrak{I}(\theta)$  to the general magnetization  $\mathfrak{I}$ .

Taking into account the magnetization definition (5.2.3)  $d\mathfrak{I}(\theta)$  we can obtain

$$d\mathfrak{I}(\theta) = \frac{\mathcal{M} \cos \theta dN(\theta)}{V}.$$

Changing in this expression  $dN(\theta)$  according to (A4.4), we can obtain

$$d\mathfrak{I}(\theta) = \frac{an\mathcal{M}}{e^a - e^{-a}} e^{a \cos \theta} \cos \theta \sin \theta d\theta.$$

The total magnetization can be found by integration

$$\mathfrak{I} = \frac{an\mathcal{M}}{e^a - e^{-a}} \int_{-1}^1 x e^{ax} dx. \quad (\text{A4.7})$$

Integration by parts ( $u = x$ ,  $dv = e^{ax} dx$ ) can give

$$\int_{-1}^{+1} x e^{ax} dx = x \frac{e^{ax}}{a} \Big|_{-1}^{+1} - \frac{1}{a} \int_{-1}^{+1} e^{ax} dx.$$

After this integration and substituting the limits:

$$\int_{-1}^{+1} x e^{ax} dx = \frac{e^a + e^{-a}}{a} - \frac{e^a - e^{-a}}{a^2}.$$

Magnetization  $\mathfrak{J}$  can now be presented as

$$\mathfrak{J} = \frac{an\mathcal{M}}{e^a - e^{-a}} \left( \frac{e^a + e^{-a}}{a} - \frac{e^a - e^{-a}}{a^2} \right) \quad \text{or} \quad \mathfrak{J} = n\mathcal{M} \left( \frac{e^a + e^{-a}}{e^a - e^{-a}} - \frac{1}{a} \right).$$

The expression in brackets is referred to as the Langevin function  $L(a)$ . Thus

$$L = \frac{e^a + e^{-a}}{e^a - e^{-a}} - \frac{1}{a}. \quad (\text{A4.8})$$

Using the function  $L(a)$  we can finally write the magnetization  $\mathfrak{J}$  as

$$\mathfrak{J} = n\mathcal{M}L(a) \quad (\text{A4.9})$$

At limiting values of  $a$  ( $\mathcal{M}B/\kappa T$ ), the  $L(a)$  function can be decomposed into the MacLoren series. At small  $a$  values we can have

$$L(a) = \frac{1}{3}a - \frac{1}{45}a^3 + \frac{2}{945}a^5 - \dots$$

This series is alternating-signed and therefore it diminishes rather quickly. If we limit ourselves to the first term, then  $L(a) \approx (1/3)a$ . The expression already given can be obtained

$$\mathfrak{J} = \frac{n\mathcal{M}^2}{3\kappa T} B.$$

The paramagnetic molar magnetic susceptibility at  $(\mathcal{M}B/\kappa T) \ll 1$  is obtained

$$\chi_M = \frac{\mu_0 N_A \mathcal{M}^2}{3\kappa T}. \quad (\text{A4.10})$$

This expression coincides with eq. (5.2.23) derived from the very simple suppositions. The volumetric and specific susceptibilities can be calculated according to the formulas given above (refer to Section 5.2.2).

# Appendix 5

## Maxwell Equations in Differential Form: Electromagnetic Wave Propagation in Vacuum

---

Vector algebra provides us with a good opportunity to write Maxwell equations in differential form, i.e., to characterize an electromagnetic field in a point. It allows us to see most clearly the physical sense of the equations and their importance for understanding the laws of electrodynamics.

Let us start with the equation of a Gauss law, which in the integral form looks like:

$$\oint_S \mathbf{D} d\mathbf{S} = \int_V \rho(r) dV. \quad (\text{A5.1})$$

Remember that in differential form, the divergence of a vector  $\mathbf{D}$  in a point  $\mathbf{r}$  is the limit to which the left-hand side of this equation tends under a contraction  $S$  (and  $V$ ) to a point:

$$\lim_{\Delta V \rightarrow 0} \frac{1}{\Delta V} \oint \mathbf{D} d\mathbf{S} = \text{div } D(r). \quad (\text{A5.2})$$

The symbol  $\text{div}$  means the sum of first particular derivatives. Therefore,

$$\text{div } D(r) = \left( \frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z} \right) D(xyz) = \nabla D(r).$$

Here an operator  $\nabla$  is introduced, well known in mathematics

$$\nabla = \mathbf{i} \left( \frac{\partial}{\partial x} \right) + \mathbf{j} \left( \frac{\partial}{\partial y} \right) + \mathbf{k} \left( \frac{\partial}{\partial z} \right).$$

Correspondingly,  $\text{div} D(r)$  is the scalar product of an operator  $\nabla$  and a vector  $\mathbf{D}(\mathbf{r})$ . In fact, the divergence is the flow of  $\mathbf{D}$  vector “outflows” from a point  $\mathbf{r}$ . Integrating the divergence

over the whole volume  $V$ , we arrive at the total power of the source, i.e., the flow through the closed surface  $S$  comprising the volume  $V$ .

$$\int_V \operatorname{div} D(\mathbf{r}) dV = \oint_S D dS.$$

This equation is referred in mathematics as the Ostrogradski theorem, from which an important expression originates:

$$\operatorname{div} \mathbf{D}(\mathbf{r}) = \rho(\mathbf{r}). \quad (\text{A5.3})$$

*The divergence of a vector of an electric displacement in a point  $\mathbf{r}$  ( $x, y, z$ ) is equal to the density of an electric charge (that is the source power of the electrostatic field) in this point.* This is the Gauss theorem in differential form. It follows that the force lines of an electrostatic field proceed from a positive electric charge (a source), come to an end in a negative electric point charge (a drain) or go to infinity; at the drain divergence has a negative sign.

Previous consideration (see Chapter 5) shows that there are no magnetic charges in nature, therefore one can write

$$\operatorname{div} \mathbf{B}(\mathbf{r}) = 0, \quad (\text{A5.4})$$

This expression is also a Maxwell equation. Hence, the magnetic field force lines are closed.

The next Maxwellian equation is the law of electromagnetic induction. This equation describes the nature of producing the electric field  $\mathbf{E}$  by variation of the magnetic field induction  $\mathbf{B}$

$$\int_L \mathbf{E} d\mathbf{l} = - \int_S \left( \frac{\partial \mathbf{B}}{\partial t} \right)_n d\mathbf{S}. \quad (\text{A5.5})$$

Note that a rotor of vector  $\mathbf{E}$  in a point  $\mathbf{r}$  is the limit of the ratio of the electric field circulation  $E$  over the closed contour  $L$ , comprises an area  $\Delta S$ , to the area  $\Delta S$  while aspiring tightening contour  $L$  (and area  $\Delta S$ ) to zero (see Figure 5.11), that is

$$\lim_{\Delta S \rightarrow 0} \frac{1}{\Delta S} \oint_L \mathbf{E} d\mathbf{l} = \operatorname{rot} \mathbf{E}(\mathbf{r}). \quad (\text{A5.6})$$

Integrating  $\operatorname{rot} \mathbf{E}$  upon surface  $\Delta S$ , we obtain circulation of vector  $\mathbf{E}$  along a contour that comprises this area

$$\oint_L \mathbf{E} d\mathbf{l} = \int_S \operatorname{rot} \mathbf{E} d\mathbf{S}.$$

In mathematics this equation is referred to as Stokes' theorem. Comparing this expression with (A5.5),

$$\text{rot } E(\mathbf{r}) = -\frac{\partial B(\mathbf{r})}{\partial t} = \dot{B}(\mathbf{r}), \quad (\text{A5.7})$$

that is, *the rotor of the electric field strength in point  $\mathbf{r}$  is equal to the time derivative from the magnetic induction in the same point.* This implies that the induction electric field is a curling (vortical) field in contrast to the electrostatic potential field. Using the previous notions, we can write instead of  $\text{rot } \mathbf{E}$  the vector product  $\nabla$  and  $\mathbf{E}$ , that is  $[\nabla \mathbf{E}] = -\dot{\mathbf{B}}(\mathbf{r})$ .

In the same way the next Maxwellian equation can be derived which connects the circulation of magnetic field strength and currents. It has the form  $\text{rot } \mathbf{H}(\mathbf{r}) = -\dot{\mathbf{D}}(\mathbf{r}) + \mathbf{j}_{\text{cond}}(\mathbf{r})$ . There are no electric currents in vacuum ( $\mathbf{j}_{\text{cond}} = 0$ ), therefore, the equation simplifies to

$$\text{rot } \mathbf{H}(\mathbf{r}) = -\dot{\mathbf{D}}(\mathbf{r}) \quad (\text{A5.8})$$

This means that the *source of the magnetic field in the point  $\mathbf{r}$  is the time changeable electric field (in the same point  $\mathbf{r}$ ).*

It is expedient to put all equations analyzed above together.

$$\begin{aligned} \text{div } \mathbf{D}(\mathbf{r}) &= \rho(\mathbf{r}), & \text{rot } \mathbf{E}(\mathbf{r}) &= -\dot{\mathbf{B}}(\mathbf{r}) \\ \text{div } \mathbf{B}(\mathbf{r}) &= 0 & \text{rot } \mathbf{H}(\mathbf{r}) &= -\dot{\mathbf{D}}(\mathbf{r}) \end{aligned} \quad (\text{A5.9})$$

To these equations it is expedient to add two, which connect the strength of both fields in vacuum and fields in an isotropic medium

$$\mathbf{B} = \mu_0 \mu \mathbf{H}, \quad \mathbf{D} = \varepsilon_0 \varepsilon \mathbf{E}. \quad (\text{A5.10})$$

The last equations are equitable only for isotropic media. In anisotropic media they have a tensor character.

The last equation in the Maxwellian system is the relation between the strength of an electric field in a point  $\mathbf{r}$  with the current density in the same point (Ohm's law in differential form)

$$\mathbf{j} = \sigma \mathbf{E}. \quad (\text{A5.11})$$

In these equations all electrodynamics is described!

Try to estimate an electromagnetic wave's propagation speed based on the Maxwellian treatment of electrodynamics. As usual, let us make the task simpler, i.e., we shall analyze a

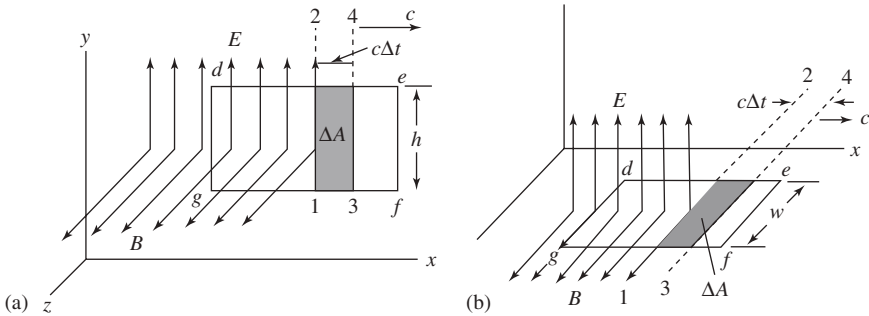
certain physical model and look to see how far it corresponds with accepted representations. In this case our problem is the definition of the speed of propagation of an electromagnetic wave in vacuum. The Maxwell equation can be written in the form:

$$\oint_L E_\ell d\ell = -\left(\frac{\partial\Phi_B}{\partial t}\right), \quad (\text{A5.12})$$

$$\oint_L B_\ell d\ell = -\left(\frac{\partial\Phi_E}{\partial t}\right) = \mu_0 \int_S \left(\frac{\partial D}{\partial t}\right) dS = \mu_0 \epsilon_0 \int_S \left(\frac{\partial E}{\partial t}\right)_n dS. \quad (\text{A5.13})$$

Let us imagine an electromagnetic wave as successive steps of “constant” electric and magnetic fields (with vectors  $\mathbf{E}$  and  $\mathbf{B}$  fixed in their magnitudes, perpendicular to each other), running along an  $x$ -axis with planes of vectors oscillation  $\mathbf{E}$  in  $x0y$  and  $\mathbf{B}$  in  $x0z$  (see Figure A5.1(a)) with a “wave” front motion speed, which we should define. Consider that in some instances, the front of the “wave” reaches line 1–2. Allocate to planes  $x0y$  an imaginary rectangular contour  $defg$  and estimate the vector  $\mathbf{B}$  flux through an area limited by the contour (Section 5.1.6, eq. (5.1.38)). In time  $dt$  the line 1–2 displaces to positions 4–3. The area  $\Delta A$  limited by the specified contour is  $\Delta A = c\Delta t \times h$ , where  $h$  is the length of segment 1–2 and  $c\Delta t$  is the distance run by the front of the “wave” in time  $\Delta t$ . As the vector  $\mathbf{B}$  everywhere is perpendicular to the plane  $x0y$ ,

$$\frac{d\Phi_B}{dt} = B\left(\frac{dA}{dt}\right) = \frac{Bhc dt}{dt} = Bhc \quad (\text{A5.14})$$



In contrast, the circulation of the  $\mathbf{E}$  vector along the contour 1–2–4–3, i.e., the left-hand side of eqs. (5.1.38, 5.4.6, 5.4.7 and A5.12), is equal to  $Eh$ . Therefore

$$\oint_L E_\ell d\ell = -Eh, \quad (\text{A5.15})$$

since  $E = 0$  on the segments 2–4, 4–3 and 3–1 (the wavefront has not yet reached them). From a comparison of eqs. (A5.14), (A5.15) and (A5.12), we can derive the ratio between  $E$  and  $B$ :

$$E = cB. \quad (\text{A5.16})$$

Continuing to consider the same model, look what occurs in the plane  $x0z$  (Figure A5.1(b)). Again we shall allocate a rectangular contour (into planes  $x0z$ ) and we shall make the same calculations as in the previous case. Using eq. (5.1.2), circulation of the vector  $\mathbf{B}$  (A5.13) gives  $Bw$  ( $w$  is the length of segment 2–4); the vector  $\mathbf{E}$  flux through area  $\Delta A$  (that is  $\Delta\Phi_E$ ) gives  $\mu_0\varepsilon_0wc\Delta t$ . Time derivation and successive cancellation on  $w$  gives

$$B = \mu_0\varepsilon_0Ec. \quad (\text{A5.17})$$

If we substitute in this equation the  $E$  value from (A5.17) and canceling by  $B$  we obtain  $\mu_0\varepsilon_0c^2 = 1$ . Whence

$$c = \frac{1}{\sqrt{\mu_0\varepsilon_0}}. \quad (\text{A5.18})$$

Three basic constants of electrodynamics appear connected with each other. Substituting values  $\mu_0$  and  $\varepsilon_0$ , we obtain for light speed in vacuum  $c = 2.998 \times 10^8$  km/sec. The agreement of this value with that obtained experimentally was a triumph of Maxwell' theory.

A similar result can be obtained with a more exact model. It is also not so difficult to show that propagation of electromagnetic waves in a medium with dielectric susceptibility  $\varepsilon$  and magnetic susceptibility  $\mu$  occurs with the speed

$$v = \frac{1}{\sqrt{\mu_0\varepsilon_0\mu\varepsilon}} = \frac{c}{\sqrt{\mu\varepsilon}} \quad (\text{A5.19})$$

Since the refraction index is the ratio of the light propagation in a medium to that in a vacuum

$$n = \frac{1}{\sqrt{\mu\varepsilon}} \quad (\text{A5.20})$$

This page intentionally left blank



# Glossary of Symbols and Abbreviations

---

This glossary is intended to free the main text from multiple repetition of the explanation of the notation used. As a rule, an explanation is given on its first occurrence in the text and occasionally elsewhere. Since the vocabulary of physics is very broad, as well as the whole range of Greek letters, the same roman letters have been used several times, partly in different fonts. Vector values are given in bold.

## Roman letters:

<b>A</b>	force work
<b><i>a</i></b> , <i>a</i>	acceleration
<b><i>a</i></b> , <b><i>b</i></b> , <b><i>c</i></b>	lattice periods
<b>B</b>	vector of magnetic field induction
<b>C</b>	heat capacity of a body, system
<b><i>C</i><sub>sp</sub></b>	specific heat capacity
<b><i>C</i><sub>M</sub></b>	molar heat capacity
<b>D</b>	vector of electric field displacement (induction)
<b><i>D</i></b>	diffusion coefficient
<b><i>d</i></b> , <b><i>d</i><sub>hkl</sub></b>	crystallographic interplanar spacing
<b><i>d</i><sub>≅Φ</sub></b>	molecule's effective diameter
<b>E</b>	vector of electric field strength
<b><i>e</i></b> , <b> <i>e</i> </b>	absolute value of the electron charge (elementary charge)
<b><i>e</i></b>	logarithmic natural base (exp)
<b><i>e</i></b>	thermal efficiency
<b><i>E</i></b>	energy, total mechanical energy
<b><i>E</i><sub>F</sub></b>	Fermi energy
<b>F</b>	vector of force
<b><i>f</i>(<b>v</b>)</b>	Maxwell molecular velocity distribution
<b><i>f</i>(<b>ε</b>)</b>	molecule kinetic energy distribution
<b><i>g</i></b>	free fall acceleration vector
<b><i>g</i></b>	gyromagnetic ratio, Lande factor
<b>H</b>	vector of magnetic field strength
<b><i>h</i></b>	Planck's constant
<b><i>h, k, l</i></b>	Miller indexes
<b><i>I</i></b>	electric current, moment of inertia (MI), intensity
<b><i>I</i><sub>z</sub></b>	moment of inertia relative to z-axis
<b><i>i</i></b>	number of degrees of freedom
<b><i>i</i></b>	imaginary unit
<b><i>i, j, k</i></b>	unit vectors (orts) of Cartesian coordinate

<b>j</b>	vector of energy density
<b>k</b>	wavevector ( $ \mathbf{k} =k=2\pi/\lambda$ )
<b>K</b>	kinetic energy, degrees of absolute thermodynamic temperature, performance factor
$\kappa$	Boltzmann constant
<b>L</b>	angular momentum's vector
$L_z$	angular momentum relative to axis z
$l, \ell$	length, distance
<b>M</b>	molar mass
<b>M</b>	vector of force moment (torque)
$M_z$	force moment relative to axis z
<b>M</b>	vector of the magnetic dipole moment, electron atomic orbit or spin moment, nuclear magnetic moment
$m$	mass of a body, atom, molecule, total system's mass
$n$	concentration
<b>n</b>	a unit vector of a normal
$N_A$	Avogadro's number
$\Pi$	a molar polarization
<b>p</b>	vector of the electric dipole moment
<b>p</b>	vector of momentum, pressure
<b>P</b>	power
<b>Q</b>	heat, activation energy
$Q, q$	electric charges
$R(\mathbf{r})$	a radial part of atomic wavefunction
<b>R</b>	molar refraction, heat emittance
$\mathbf{r}(x, y, z)$	Cartesian radius vector
$\mathbf{r}(r, \theta, \varphi)$	radius vector in a spherical coordinate system
<b>S</b>	area
<b>S</b>	entropy
$s$	wave polarization index
<b>T</b>	absolute thermodynamic temperature
$t, \tau$	time
<b>T</b>	period
<b>U</b>	potential energy
<b>U</b>	internal energy of a molecular system
<b>V</b>	volume
$V_M$	molar volume
$\langle v \rangle$	average speed of a particle
$v_{\text{rms}} = \sqrt{\langle v^2 \rangle}$	root mean square of a particle's speed
$v_{\text{prob}}$	most probable value of a particle's speed
<b>v</b>	velocity vector
<b>W</b>	thermodynamic probability
$Y(\theta, \varphi) = \Theta(\theta)\Phi(\varphi)$	angular part of the atomic wave function
<b>Z</b>	statistical sum

**Greek letters:**

$\alpha$	angle, molecular polarizability
$\beta$	angle, a force constant
$\beta=v/c$	the relative speed coefficient in special relativistic theory
$\gamma$	coefficient of anharmonicity; adiabatic index
$\delta$	attenuation coefficient
$\varepsilon$	dielectric susceptibility, a micro-object energy
$\langle \varepsilon \rangle$	average kinetic molecular energy
$\boldsymbol{\varepsilon}$	angular acceleration vector, thermal process efficiency
$\varepsilon_0$	electric constant
$\langle \varepsilon_{\text{osc}} \rangle$	average energy of atomic oscillations in molecules
$\langle \varepsilon_{\text{rot}} \rangle$	average energy of molecule rotation
$\eta$	coefficient of dynamical viscosity, coefficient of kinematic viscosity
$\kappa$	dielectric permeability, coefficient of molecular heat transfer
$\lambda$	wavelength, logarithmic attenuation decrement, mean free path length
$\mu$	magnetic permeability, reduced molecular mass
$\mu_0$	magnetic constant
$\mu_B$	Bohr magneton
$\mu_N$	nuclear magneton
$\nu$	coefficient of kinematic viscosity, frequency ( $\nu = n$ - speed of rotation)
$\xi$	displacement from equilibrium position
$\rho$	density of matter, electron density
$\sigma$	surface charge density
$\boldsymbol{\tau}$	unit vector of a tangent
$\tau$	system's time of life, relaxation time, linear charge density
$\boldsymbol{\omega}$	angular velocity, $\omega = 2\pi\nu$
$\psi(x,y,z)$	time-independent wave function
$\Psi$	magnetic flux linkage/time-dependant wave function
$\Phi$	flux
$\varphi$	angle, electric field potential
$\chi$	magnetic susceptibility time-dependent wave function
$\Omega$	solid angle

**Others fonts:**

$\mathfrak{M}$	magnetization
$\mathfrak{R}$	polarizability (polarization vector)
$\wp$	surface density of electrical current

**Quantum numbers:**

$n, \ell, m_\ell, s, m_s$	quantum numbers of one-electron atom
$L, m_L, J, m_J, S, m_s$	quantum numbers of multielectron atom
$I, m_I$	nuclear quantum numbers
$s, p, d \dots$	one-electron states
$S, P, D \dots$	many-electron atoms states

$v$	a molecule vibrational quantum number
$j$	a molecule rotational quantum number

**Abbreviations:**

MP	material point
CM	center of mass
MI	moment of inertia
IRB	ideal rigid body
IBB	ideal black body
SF	superfine

# Index

## A

A, *see* Ampere  
Absolute zero  
  temperature 177  
Absorption spectrum 492  
Acceleration  
  angular 12, 14, 40  
  average 4  
  center of mass 12  
  centripetal 25, 183  
  constant 9  
  due to gravity 20, 30, 587  
  in electric field  
  in simple harmonic motion 108  
  instant 4  
  radial (normal) 7  
  tangential 5, 7, 14  
Activation energy 186, 194, 446  
Adiabatic process  
  adiabatic index 199  
  with ideal gas 199  
Alpha particle 325  
Alternating current 305  
Ampere (unit)  
  definition 583  
Ampere's law 318  
Ampere–Maxwell law 351  
Amplitude 107, 112  
Angle  
  of incidence 363  
  of polarization 390  
  of reflection 363  
  of refraction 363  
Angular  
  acceleration 13, 14  
  displacement 12–14  
  force  
    moment 51  
    torque 51, 52  
  frequency 107, 157  
  momentum 40, 41, 48–50  
  conservation of 71

  orbital 332  
  spin 460, 498  
  vector form velocity 15  
  velocity 13, 14, 41  
Antinode 158, 159  
Approximations 76, 439  
Archimedes's buoyant force 127  
Area, units of 581  
Atmosphere (unit) 171  
Atmosphere of earth 182, 406  
Atom 332  
Atomic mass unit 498  
Atomic number 460  
Avogadro constant 297, 339, 587

## B

B, *see* Magnetic field induction  
Barometric height distribution function 181–182  
Beatings 117  
Binding energy 512  
Biot–Savart law 311  
Birefringence 391  
Bloch function 539  
Bohr atom model 416–419  
Bohr magneton 454, 586  
Boltzmann constant 176, 219, 587  
Boltzmann distribution  
  at different temperatures 179, 181  
Boltzmann factor 185–186, 551  
Boson 542  
Bragg's law 386  
Brewster's law 388–389

## C

C, *see* coulomb  
Conservation law  
  of charge 251  
Capacitor  
  displacement current in 254  
  parallel-plate 253, 254

- Carnot
    - cycle 207–210
    - engine 211
    - microcycles 211
  - Celsius temperature 177
  - Center of mass
    - acceleration of 12
    - of two particles 36
    - rigid body 47
    - symmetry and 37
  - Centripetal acceleration 35, 183, 185
  - Centripetal force 184, 185
  - Charge
    - interaction force 75
    - unit 584
  - Chemical potential 542
  - Chemical shift 504–506
  - Chemical shift in IFRS 514
  - Chemical shift in NMR 520
  - Circuit, electrical 307, 308
  - Critical angle
    - total internal reflection 364
  - Clausius inequality
    - entropy change 215
    - in nonequilibrium processes 214–216
  - Coherence 170
  - Collision
    - center of mass 80
    - conservation of 79
    - conservation of energy in 81
    - elastic 80
    - head to head 80, 81
    - inelastic 88
    - momentum in 81
    - one-dimensional 81
  - Complex variable 110, 111
  - Conductivity
    - electrical 280, 352
    - thermal 233, 236
  - Configurational space 541
  - Conservation energy law in thermodynamics 196
  - Conservation laws
    - in collisions 79
    - of angular momentum 71
    - of energy 74
    - of linear momentum 69
    - of mechanical energy 67
  - Conservative force 60
  - Constant-pressure process 198
  - Constant-volume process 198
  - Convection 181, 237
  - Cooper's pairs 543
  - Coordinates, space-time 39
  - Coordination
    - number 567
    - sphere 567
  - Coulomb 584
  - Coulomb's law 252
    - and Gauss' law 259–263
  - Crystal class 533
  - Crystal lattice 531–536
    - periods 556
  - Crystal structure 531–536
  - Crystallographic direction 535
  - Crystallographic plane 533–535
    - interplanar spacing 535
  - Curie point 345, 575
  - Curie temperature 346, 347, 575
  - Current
    - alternating 305
    - charge carrier of 251, 280
    - displacement 350–354
  - Current density 306, 307
  - Current drift speed 306
  - Current loop
    - as magnetic dipole 319
    - as magnetic moment 348
  - Cycles
    - direct 205
    - reversed 205
  - Cyclic process
    - nonreversible 214–216
    - reversible, as Carnot cycles 206, 207
- D**
- Damped harmonic motion
    - energy 131–133
  - Damped oscillations 133–138
  - Debye unit 276
  - Deceleration 85, 473
  - Degree of freedom 106
  - Density
    - electron density 285, 287, 288
    - linear 251, 263
    - surface 251, 262, 270, 283
    - volume, 251

- Deuteron 86, 527
  - Diamagnetics 331, 337
  - Dielectric hysteresis loop 575
  - Dielectrics 280–282
  - Diffraction
    - by grating 381–383
    - by single slit 379–381
    - Fraunhofer 379, 380
    - Huygens–Fresnel principle 378–379
    - of electrons 424–426
    - of neutrons 424–426
    - types of 379
    - X-ray 385–386
  - Diffraction grating 381–383
  - Diffusion
    - coefficient  $D$  235
    - Fick's law 235
  - Dipole, electric, *see* Electric dipole
  - Dipole, magnetic, *see* Magnetic dipole
  - Dipole–dipole interaction 280
  - Dispersion
    - of grating 383, 384
    - of light 395–398
  - Dispersion curves 545–550
    - acoustic branch 546, 548
    - optic branch 546, 548
  - Displacement
    - of simple harmonic motion 108
  - Displacement current
    - in capacitor 351
  - Distribution function calculation
    - average value 172–174
  - Domains, ferroelectric 575
  - Domains, ferromagnetic 347–349
  - Doppler effect
    - acoustic 154–156
    - for light 154
  - Drift speed of carrier 306
- E**
- E, *see* Electric field
  - Earth
    - mass 62
  - Earth–moon system 99
  - Efficiency of engine 207, 209, 210
  - Elastic collision 80, 412
  - Electrets 576
  - Electric charge 251, 273, 305
    - Electric current 305–309
    - Electric charge
      - in dielectrics 281
    - Electric dipole
      - moment 276
      - potential energy 278–279
      - torque on 278
    - Electric displacement 284, 584
    - Electric field
      - equipotential surfaces 275
      - flux of 261
      - induced 353
      - induced magnetic field 353
      - lines of force 253, 254
      - of electric quadrupole 501
      - of electromagnetic wave 33
      - of finite rod 256–257
      - of infinite cylinder 270
      - of infinite line 256–257
      - of infinite plate 263–264
      - of point charge 253, 254
      - of ring 258–259
      - of semi-infinite rod 300–301
      - of spherically symmetric charge 252, 267, 275
      - potential 29
    - Electric field potential
      - capacitor 276
      - dipole 276–288
      - distribution of charge 251
      - of system of charges 274
      - point charge 274
      - ring 259
    - Electric potential
      - superposition principle 274
    - Electric quadrupole moment 501–502
    - Electric strength flux 261
    - Electromagnetic force 29, 31
    - Electromagnetic induction 328–331
    - Electromagnetic radiation 353
    - Electromagnetic spectrum 354
    - Electromagnetic waves
      - amplitudes of fields 353
      - energy density in 353
      - from dipole 353
      - Poynting vector 353
      - scale 354
      - sources of 351
      - speed of 353

wave equations 352–353  
*See also* Light  
 Electromotive force 308  
 Electron  
   charge to mass ratio 325  
   magnetic dipole moment 332  
   orbital dipole moment 332  
   spin angular momentum 332  
 Electrons as quasi-particles 540  
 Electron paramagnetic resonance (EPR)  
   526–529  
 Electrons in crystals 537–545  
 Electrostatics 251–252  
 Electrostriction 572  
 Elevator, weight in 30  
 EMF, *see* Electromotive force  
 Energy  
   activation 186, 446, 447  
   binding 512  
   conservation 196  
   quantization of 457  
   quantized level 437–438  
   relationship with mass 97  
   rest 96  
   SI units of 582  
   simple harmonic motion 105  
 Energy density  
   of electromagnetic radiation 353  
 Engine  
   efficiency of 207  
 Entropy  
   changes in 213  
   irreversible process 214–216, 220  
   reversible process 211, 212, 216, 220  
   statistical definition 212  
 Equation of state, ideal gas 175  
 Equilibrium in thermodynamics 169, 170, 230  
 Equipotential surface 275  
 Equipartitioning of energy  
   on degree of freedom 194–195  
 Extraneous force 308

## F

F, *see* Farad  
 Fahrenheit temperature 177  
 Farad 585  
 Faraday 328–330, 587  
 Faraday's law, *see* Electromagnetic induction

Fermi level 541  
 Fermion 541  
 Ferroelectrics (segnetoelectrics) 574, 575  
 Ferromagnetism 344–347  
 Fiber light guides 364  
 Fine interaction 467–468  
 Fine structure constant 468  
 First law of thermodynamics 194–205  
   in various processes 196, 197  
 Flux of  
   electric field strength 261  
   magnetic field induction 328, 329  
   vector field 259, 328  
 Force  
   as vector 20, 40  
   centripetal 185, 321  
   conservative 60  
   derived from potential energy 61, 63  
   dissipative 60  
   external 28, 52, 53  
   internal 53  
   non-conservative 60  
   unit of 582  
 Force constant 545, 546  
 Force fields 58–61  
 Forced oscillations 138–145  
 Fraunhofer diffraction 379, 380  
 Free expansion 196  
 Free fall acceleration 18, 20, 587  
 Free path length 235  
 Frequency  
   and period 107  
   angular 107  
   of string vibration 160–161  
   resonant 140  
   simple harmonic motion 108  
   units of 581  
 Friction  
   non-conservative nature 32, 238  
 Fresnel diffraction 378–379  
 Fuel combustion 26–28, 206

## G

Galilean transformation 18–20  
 Gamma-resonance (Mössbauer effect)  
   510–513  
 Gas, ideal 174  
 Gas constant  $R$ , universal 181, 587



Gauss' law  
 applied to charge distributions 259–263  
 Gauss surface 261, 262  
 General theory of relativity 90–91  
 Grating, diffraction  
 dispersion of 383  
 principal maxima of 382  
 resolving power 383, 384  
 secondary maxima 382  
 transmission 385  
 Gravitational constant 30, 587  
 Gravitational field  
 gravitational mass 30  
 gravitational potential energy 61–62, 66  
 Gravity, acceleration of free fall 18,  
 20, 587  
 Gravity of  
 earth 65, 66, 182  
 moon 182  
 Ground state 362  
 Group speed 398

**H**

H, *see* Henry  
 Harmonic motion  
 damped 133–138  
 forced simple 138–145  
*See also* Simple harmonic motion  
 Harmonic oscillator 76, 129–131  
 Heat  
 engine 206–207  
 pump 210–211  
 Heat capacity of crystals  
 Debye model 552  
 Debye frequency 553, 554  
 Debye function 553, 554  
 Debye temperature 55, 554  
 Dulong–Petit law 551  
 Einstein model 551  
 Heat capacity of ideal gas  
 in dissociation 202  
 versus experiment 204–205  
 Heat transport coefficient  $\kappa$  237  
 Henry 587  
 Hertz 581  
 Hooke's law 31  
 and potential energy 31, 62  
 elastic force work 52

Huygens' principle  
 diffraction 378–379  
 Hydrogen atom 416–419  
 Hysteresis loop  
 in ferroelectrics 575  
 in ferromagnetics 348, 349  
 Hz, *see* Hertz

**I**

Ideal gas  
 adiabatic process 199  
 and temperature 197  
 at constant pressure 213  
 at constant volume 213  
 average energy 176  
 general equation 175  
 heat capacities 197–204  
 in force field 178–180  
 internal energy 195  
 isotherms 200, 207, 208, 211  
 model 174  
 pressure 175  
 Impulse of force 21  
 Incidence, plane of 388  
 Index of refraction 297, 361, 363–365, 388,  
 392, 395, 396  
 total internal reflection 364, 393  
 Induced electric field, *see* Electromagnetic  
 induction  
 Induced EMF 329, 330  
 Induced magnetic fields 309–313  
 Inductance  
 mutual 330  
 of solenoid 331  
 self 330  
 units 587  
 Induction, Faraday's law of, *see*  
 Electromagnetic induction  
 Inelastic collision 88–89  
 Inertia, law of 17  
 Inertia, rotational 40  
 Inertial mass 30  
 Initial conditions, in harmonic motion  
 107, 108  
 Intensity  
 in single-slit diffraction 380, 381  
 wave amplitude 406  
 Interference, from thin films 370–374

Internal energy 88, 89, 195, 198  
 of ideal gas 186, 195, 196  
 of van der Waals's gas 226  
 Internal forces 35, 38, 53, 61, 63, 70  
 International System of Units, *see* SI  
 Invariance 68  
 Invariant quantities 18, 19  
 Ionic polarization 571–572  
 Irreversible process  
 entropy change of 214–216, 220  
 Isotherm 200, 207, 208, 211, 222, 223  
 Isotope 183, 220, 244, 498  
 Isotropic material 147, 284, 286, 291, 295,  
 361, 392, 576

**J**

Joule–Lenz law 328  
 Joule–Thomson effect 227–229

**K**

Kinematics 1–16  
 Kinetic energy  
 center of mass 55  
 in simple harmonic motion 131  
 in transverse wave 152  
 of rotation 47, 55  
 relativistic 96  
 Kinetic theory  
 pressure, ideal gas 175  
 temperature, ideal gas 177  
 Kirchhoff's law 401  
 Knudsen flow 244

**L**

Lattice defects  
 clusters 563  
 dislocation 563–566  
 Burgers vector 564  
 edge 564, 565  
 linear 564  
 screw 564, 565  
 small angle boundaries 565  
 interstitials 561, 563  
 point 561–563  
 Frenkel 561, 562  
 Schotky 562  
 vacancies 561, 563

Laue diffraction 385  
 Length, relativity 91  
 Lenz's law 328  
 Light  
 energy quanta 408, 409  
 momentum 412  
 polarization 386–395  
 polarized 386  
 quantization and emission of  
 387–388  
 sensitivity of eye to 361  
 speed of 392  
 unpolarized 362  
 visible 361  
 Linear density 251  
 Linear motion, with constant acceleration 7  
 Linear oscillator 129–131  
 Lines of force, electric field 275  
 Liquid crystals 576–577  
 Lorentz transformation 90

**M**

*m*, *see* meter  
 Magnetic dipole 327–328  
 Magnetic splitting 347  
 Magnetic dipole moment  
 of iron atom 347  
 of iron ions 347  
 Magnetic domain 347–349  
 Magnetic field  
 circulating charges 305  
 electric current 305–309  
 electromagnetic wave 353, 354  
 flux 336  
 induction 309–313  
 induced electric fields 330  
 strength 307, 308, 310, 311, 320, 334, 342,  
 347, 348  
 Magnetic flux 328, 330, 331  
 Magnetic force  
 between parallel wires 313  
 on moving charge 320–327  
 on wire with current 313  
 Magnetic monopole 310, 351  
 Magnetically ordered state 344–350  
 Magnetization 333, 336–344  
 Magnetron  
 Bohr 346, 453, 586, 587  
 nuclear 499, 516, 587

Magnets 348  
 Magnetic field induction 309–318, 586  
 Mass  
   and energy 96, 97  
   and weight 30  
   atomic unit of 587  
   center of 36–38  
   equivalence principle 96, 97  
   gravitational 30  
   inertial 30  
   in relativity 91  
 Mass number 323, 498  
 Mass spectrometry  
   mass spectrometer 322, 323  
 Maxwell's equations 599–603  
 Maxwell energy distribution function 193–194  
 Maxwell velocity distribution function  
   average 188, 189  
   most probable 188, 189  
   on molecular energy 189  
   root square mean 188, 189  
 Maxwell's law 186–190, 195, 599–603  
 Mean free path 242  
 Mechanical energy  
   kinetic 54  
   potential 61  
   potential energy curves 74–79  
 Miller indexes 534  
 Molar heat capacity  
   at constant pressure 198  
   at constant volume 198  
   of ideal gases 198, 213  
 Molecular speeds 187, 188  
 Molecular mass 88, 131  
 Moment of inertia 40–43  
 Momentum  
   and Newton's second law 20–29  
   angular, *see* Angular momentum  
   conservation of 69, 71  
   kinetic energy 68  
   relativistic 91  
   velocity of center of mass 38  
 Moon 182  
 Mössbauer effect 510–513  
 Mössbauer spectroscopy 508–516  
 Mount Everest, potential energy 66  
 Mutual inductance  
   units of 87  
 Mutual induction 330

## N

N, *see* Newton  
 Nanoparticles 555–557  
 Natural frequency 140, 141, 396  
 Natural width of spectral line 510  
 Negative charge 253, 288  
 Neutral matter 251, 280, 342, 426, 497, 499  
 Neutron 425, 489, 497, 499  
 Newton 582  
 Newton rings 374  
 Newton's first law 16–18  
 Newton's law of gravity 30  
 Newton's second law  
   angular form 21  
   for particle 21  
   for system 22  
   in relativity 21, 95  
   momentum form 21  
   simple harmonic motion 119  
 Newton's third law 29  
 Node 158, 159  
 Nonconservative forces 60  
 Nuclear forces 497, 499, 500  
 Nuclear magnetic resonance (NMR)  
   516–525  
   proton magnetic resonance (PMR) 518, 521  
 Nuclear magnetism 516–525  
 Nuclear physics  
   nucleon model of nucleus 497–499  
 Nuclear quadrupole resonance (NQR) 525  
 Nucleon  
   energy levels 499–500  
   form 500, 501  
   magnetic moment 499  
   mass 498  
   nuclear gyromagnetic ratio 498  
   nuclear magneton 499  
   quadrupole moment 501–502  
   size  
     charge distribution radius 500–501  
     mass distribution radius 500–501  
   symmetry 500  
 Nucleus 332, 497–499

**O**  
 Ohm's law 307, 352  
 Orbital magnetic dipole moment 333,  
   342, 453

- Order
  - long range 568
  - short range 568
- Oscillation, center of 122
- Oscillations
  - damped 133–138
  - forced 138–148
  - simple harmonic 106–113
- P**
- Pa, *see* Pascal
- Parallel axis theorem 43–44
- Paramagnetism 332, 340, 343
- Pascal 582
- Path independence and conservative forces 60
- Pendulum
  - physical 121–122
  - simple, mathematical 119–121
  - spring 118–119
- Performance, thermal coefficient of 210
- Period
  - and frequency 107
  - of linear oscillator 119, 120, 122
  - of simple harmonic motion 132
- Permanent magnetism 348
- Permeability constant 309–310
- Permittivity constant 293
- Perovskite type crystal 575, 576
- Perpendicular axis theorem 45
- Phase
  - of simple harmonic motion 107
- Phase changes, on reflection 160, 368
- Phase difference, in interference 370
- Phase speed 151, 398, 546
- Photo-effect external
  - Einstein photo-effect law 407, 408
- Physical kinetics
  - collision cross-section 232
  - effective diameter at collisions 231
  - relaxation process, time of 230–231
- Physical model 35
- Physical pendulum 121–122
- Physics, quantum 33, 479, 490, 510, 541
- Piezoelectric effect 572–574
- Piezoelectrics 572–574
- Planck constant 404, 587
- Planes, mirror 35
- Plane motion 2
- Plane of incidence 388
- Plane polarization 390
- Polar material 280, 284, 291, 297
- Polarization
  - dielectric 286–292
  - reflection 388–389
- Polarization of electromagnetic waves 362, 386–394
- Polarized light
  - plane 387, 389
  - reflection 388–389
- Polarizer 387–388
- Polarizing angle 390
- Postulate
  - relativity 90
  - speed of light 90
- Potential, electric, *see* Electric field potential
- Potential energy
  - and work 61
  - electric 75
  - electric dipole 278
  - force 63
  - gravitational 62, 74
  - magnetic dipole 327
  - simple harmonic oscillator 131
- Potential–energy curve 74–79, 186, 482
- Potential difference 276
- Power
  - average 53
  - instantaneous 54
  - units of 582
- Poynting vector 353
- Precession 51, 337, 338, 477, 589–590
- Pressure, kinetic theory of 175, 176
- Prism 364, 365, 384, 391
- Process
  - adiabatic 199
  - cyclic 205
  - constant volume 198
  - irreversible 206
  - isobaric 198
  - reversible 206
- Projectile motion 9
- Proton 497–499
- Pyroelectric effect 572
- Q**
- Quadrupole moment 501, 584, 593
- Quadrupole resonance 525
- Quadrupole splitting 506

- Quantization
  - at emission of light 512
  - electron energy in atom 457–460
  - of angular momentum 455, 456
- Quantum mechanics 423–496
- Quartz crystal oscillator 137
  
- R**
- R (universal gas constant) 181, 487
- Radial distribution function 567
- Radian 581
- Radiation, blackbody 398–402
- Ratio of specific heats for gases 199
- Ray 147
- Rayleigh's criterion 384
- Real gas approximation
  - corresponding states law 225
  - critical point 223
  - internal energy of 226
  - Joule–Thomson effect 227–229
    - inversion curve 229
    - inversion point 229
  - phase diagram of state 223, 224
  - van der Waals gas 221–226
    - real isotherms of 223
  - van der Waals equation 221, 222
    - in reduced parameters 225
- Recoil 511, 512
- Reduced amount of heat: entropy change
  - in isobaric process 213
  - in isochoric process 213
- Reference frames 21, 97
- Reference system (frame) 1
  - Inertial 16
  - Noninertial 33
- Reflection
  - law of 363
  - phase change 368
  - polarization 388–389
  - thin film 371, 372
  - total internal 364
- Refraction
  - Huygens' principle 378–379
  - index of 361, 363, 365
  - law of 363
- Refrigerator 210–211
- Relativity
  - motion at high speed 90
  - speed summation law 90
  - Shortening of length 91
    - dilation of time 94
    - simultaneity 94
- Resolving power
  - of grating 384
- Resonance 140, 497–529
- Resonance absorption 508–510
- Rest mass 426
- Reversible process, entropy change in 213
- Rigid body
  - angular momentum and velocity 41
- Rocket, propulsion 26, 27
- Rolling motion, energy of 57
- Root-mean-square molecular speed
  - 188, 189
- Rotation
  - angular momentum 41
  - analogy with translation motion
    - 50, 51
  - with constant acceleration 15
- Rotational motion
  - analogies to translational motion 50
  - kinematics 12
  - dynamics 16
- Rotation of plane of 389–391
- Rotator, rigid 47, 450
  
- S**
- Saturation
  - ferromagnetic 349
  - paramagnetic 341
- Second law of motion, *see* Newton's second law
- Second law of thermodynamics 205–221
  - entropy 211–214
- Selection rules 479, 480
- Self-induction 331, *see also* Inductance
- Semiconductors
  - acceptor type 544
  - donor type 544
  - intrinsic type 544
  - n-type 544, 545
  - p-type 544, 545
- SI 581
- Simple harmonic motion
  - acceleration 108
  - amplitude 107
  - angular frequency 107
  - displacement 107

equation of motion for 107  
 kinetic energy of 131  
 period of 106  
 phase 107  
 Simple harmonic oscillator  
   period of 131  
 Single-slit diffraction 379–381  
 Snell's law 363  
 Solenoid, magnetic field of 319, 320  
 Solid-state dynamics  
   Born–Karman chain 545  
 Special relativistic theory 90–97  
 Specific heat capacity 197, 198, 583  
 Speed  
   angular 57, 73  
   average 3, 8, 307, 570  
   molecular  
     average 188  
     distribution of 186–190  
     most probable 188  
     root-mean-square 188  
   radial acceleration 14  
   speed and acceleration 95  
 Speed of light 603  
 Spherical symmetry 252, 268, 269, 270, 500  
 Spin, quantum number 460, 469, 480, 498, 517,  
   518, 527, 541, 542  
 Spring scale 30  
 Spring, force law 52  
 Spring, potential energy 62  
 Standing waves 157–160  
 Statistical thermodynamics 219–220  
 Statistics  
   Bose–Einstein 542  
   classic 541  
   distribution function 541  
   Fermi–Dirac 541  
   quantum 540–543  
 Steradian 261, 581  
 String, waves on 160–161  
 Superconductivity 543  
 Superfine dipole–dipole interaction 523  
 Superfine interaction 515–516  
 Superposition  
   principle 156, 157, 274, 277  
 Surface charge 576  
 Surface current 335  
 Symmetry operation 531  
 Syngony 533

## T

T, *see* Tesla  
 Tangent, unit vector of 2  
 Tangential acceleration 14  
 Temperature  
   in kinetic theory 177–178  
 Temperature scale  
   Celsius 177  
   Fahrenheit 177  
   Kelvin 177  
   Réaumur 177  
 Tesla 586  
 Thermal conductivity 233, 236  
 Thermal energy 197, 198, 206, 406  
 Thermal equilibrium 169, 407  
 Thermodynamics  
   first law of 194–205  
   second law of 205–221  
   zeroth law of 170  
 Thermodynamic process 170, 206  
 Third law of motion 29  
 Thrust, of rocket 27, 28  
 Time  
   of settled life 568  
 Time dilation 94  
 Torque  
   and angular acceleration 48  
   and angular momentum 49  
   on electric dipole 278  
   on magnetic dipole 327  
 Total internal reflection 364  
 Trajectory of projectile 72  
 Transformation  
   Galilean 18–20  
   Lorentz 90  
   space time 90  
   velocity 91  
 Translation 531, 532  
 Translational motion and rotational motion  
   50, 51  
 Transport phenomena in ideal gases 233–235  
   flow of G property 234  
   macroscopic representations 233–235

## U

Unit cell  
   body-centered cell (BCC) 535

- face-centered cell (FCC) 535
- primitive unit cell 535
- Unit vector 2
- V**
- V, *see* Volt
- Vacuum
  - heat transfer in vacuum 243–244
- Velocity
  - angular 13, 14
  - average 3
  - in simple harmonic motion 107
  - linear 14, 41
  - transformation 18, 19
- Velocity space 187
- Viscosity (internal friction)
  - dynamical coefficient  $\eta$  239
  - kinematical coefficient  $\nu$  240
- Volt 584
- Voltage, *see* Electromotive force
- Volume, units of 581
- W**
- Water molecule 3, 45, 46, 170
- Waves
  - electromagnetic, *see* Electromagnetic waves
  - interference 369–377
  - longitudinal 146
  - mechanical 145
  - sinusoidal 159
  - standing 157–160
  - string 160–163
  - transverse 146
  - transverse simple harmonic, energy of 151–154
  - transverse standing equation of 158
  - traveling, equation of 147–151
- Wave equations 148, 150
- Wave number 149, 492
- Wave speed 155
- Wavelength 148
- Wavelength of light 354
- Wavetrain 362
- Weber 587
- Weight 30
- Wire
  - magnetic field of 313
  - magnetic force on 316
- Work–energy theorem 63
- Work of gas
  - in adiabatic process 199
  - in elementary processes 226
  - in isobaric process 198
  - in isochoric process 198
  - in isoprocesses 197–201
  - in isothermic process 200, 207
- X**
- X-rays
  - bremschtrahlung 410
  - characteristic 410
- X-ray diffraction 385–386
- Z**
- Zeeman effect 477–480
  - anomalous 477, 478
  - normal 477, 478, 480
  - nuclear 478
- Zeroth law of thermodynamics 170
- Zone theory
  - conductivity band 539
  - energy bands 539
  - forbidden energy gap 539
  - hybrid band 539
  - valence energy band 539

This page intentionally left blank