Handbook of Physics

Department of Physics, RVCE, Bengaluru

For course:
Quantum Physics for Engineers

Fundamental Constants

All the constants in this table are taken from *The NIST Reference on Constants, Units & Uncertainty* found in `http://physics.nist.gov/constants`.

Quantity	Symbol	Value	Unit
Speed of light in vacuum	c	$299\,792\,458$	$\mathrm{m\,s^{-1}}$
Magnetic constant	μ_0	$4\pi \times 10^{-7}$	$\mathrm{N\,A^{-2}}$
Electric constant $1/\mu_0 c^2$	ϵ_0	$8.854\,187\,817 \times 10^{-12}$	$\mathrm{F\,m^{-1}}$
Newtonian constant of gravitation	G	$6.673\,84 \times 10^{-11}$	$\mathrm{m^3 kg^{-1} s^{-2}}$
Planck constant	h	$6.626\,069\,57 \times 10^{-34}$	$\mathrm{J\,s}$
$h/2\pi$	$\hbar$	$1.054\,571\,726 \times 10^{-34}$	$\mathrm{J\,s}$
Elementary charge	e	$1.602\,176\,565 \times 10^{-19}$	C
Bohr magneton $e\hbar/2m_e$	μ_B	$927.400\,968 \times 10^{-26}$	$\mathrm{J\,T^{-1}}$
Nuclear magneton $e\hbar/2m_p$	μ_N	$5.050\,783\,53 \times 10^{-27}$	$\mathrm{J\,T^{-1}}$
Fine-structure constant $e^2/4\pi\epsilon_0\hbar c$	α	$7.297\,352\,569\,8 \times 10^{-3}$	
Rydberg constant $\alpha^2 m_e c/2h$	R_∞	$10\,973\,731.568\,539$	$\mathrm{m^{-1}}$
Bohr radius $\alpha/4\pi R_\infty = 4\pi\epsilon_0\hbar^2/m_e e^2$	a_0	$0.529\,177\,210\,92 \times 10^{-10}$	m
Electron mass	m_e	$9.109\,382\,91 \times 10^{-31}$	kg
energy equivalent	$m_e c^2$	$0.510\,998\,928$	MeV
Proton mass	m_p	$1.672\,621\,777 \times 10^{-27}$	kg
energy equivalent	$m_p c^2$	$938.272\,046$	MeV
Neutron mass	m_n	$1.674\,927\,351 \times 10^{-27}$	kg
energy equivalent	$m_n c^2$	$939.565\,379$	MeV

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Quantity	Symbol	Value	Unit
Avogadro constant	N_A	$6.022\,141\,29 \times 10^{23}$	$\mathrm{mol^{-1}}$
Atomic mass constant $m_u = \frac{1}{12}m(^{12}\mathrm{C}) = 1\mathrm{u}$	m_u	$1.660\,538\,921 \times 10^{-27}$	kg
energy equivalent	$m_u c^2$	$1.492\,417\,954 \times 10^{-10}$	J
		$931.494\,061$	MeV
Faraday constant $N_A e$	F	$96\,485.336\,5$	$\mathrm{C\,mol^{-1}}$
Universal gas constant	R_u	$8.314\,462\,1$	$\mathrm{J\,mol^{-1}K^{-1}}$
Boltzmann constant R/N_A	k	$1.380\,648\,8 \times 10^{-23}$	$\mathrm{J\,K^{-1}}$
Stefan-Boltzmann constant $(\pi^2/60)k^4/\hbar^3 c^2$	σ	$5.670\,373 \times 10^{-8}$	$\mathrm{W\,m^{-2}K^{-4}}$
First radiation constant $2\pi hc^2$	c_1	$3.741\,771\,53 \times 10^{-16}$	$\mathrm{W\,m^2}$
Second radiation constant hc/k	c_2	$1.438\,777\,0 \times 10^{-2}$	$\mathrm{m\,K}$
Wien displacement law			
constant $b = \lambda_{max}T$	b	$2.897\,772\,1 \times 10^{-3}$	$\mathrm{m\,K}$
constant $b' = \nu_{max}/T$	b'	$5.878\,925\,4 \times 10^{10}$	$\mathrm{Hz\,K^{-1}}$
Molar mass constant	M_u	1×10^{-3}	$\mathrm{kg\,mol^{-1}}$
Molar mass of $^{12}\mathrm{C}$	$M(^{12}\mathrm{C})$	12×10^{-3}	$\mathrm{kg\,mol^{-1}}$
Standard atmosphere		101.325	kPa
Standard acceleration of gravity	g	$9.806\,65$	$\mathrm{m\,s^{-2}}$

Quantum Mechanics

Quantity	**Formula**	**Glossary**
Planck's formula for the blackbody radiation: Power radiated per unit area per unit solid angle per unit frequency by a black body at temperature T:	$U(\nu,T) = \dfrac{8\pi h\nu^3/c^3}{\left[\exp\left(\frac{h\nu}{kT}\right) - 1\right]}$	h = Planck constant c = speed of light in vacuum k = Boltzmann constant ν = frequency of the electromagnetic radiation

Einstein's fundamental equation for photoelectric effect:	$E_K = h\nu - \Phi$	E_K = kinetic energy of the ejected electron ν = frequency of photon Φ = work function of the metal
Energy of the discrete emission or absorption of radiation by atoms:	$h\nu = \lvert E_i - E_f \rvert$	E_i = initial state energy E_f = final state energy
Energy of the emitted photon:	$E = h\nu = \dfrac{hc}{\lambda}$	λ = wavelength of the emitted photon
Compton formula:	$\lambda' - \lambda = \dfrac{h}{m_e c}(1 - \cos\theta)$	λ = wavelength of the incident photon λ' = wavelength after scattering m_e = electron rest mass c = speed of light θ = scattering angle
Compton wavelength of the electron:	$\lambda_e = \dfrac{h}{m_e c} = 2.43 \times 10^{-12}$ m	
Compton formula in terms of the energies:	$E_{\gamma'} = \dfrac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2}(1 - \cos\theta)}$	$E_\gamma = hc/\lambda$ = incident energy $E_{\gamma'}$ = scattered photon energy
de Broglie wavelength:	$\lambda = \dfrac{h}{p}$ $\lambda = \dfrac{h}{\sqrt{2mqV}}$	p = momentum of the particle m = mass of the particle q = charge of the particle V = potential with which the particle is accelerated
Phase velocity:	$v_p = \dfrac{\omega}{k} = \nu\lambda$	ω = angular frequency $k = 2\pi/\lambda$ = wave number ν = frequency
Group velocity:	$v_g = \dfrac{d\omega}{dk}$	

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Relation between group velocity and phase velocity:	$v_g = v_p - \dfrac{2\pi}{k}\left(\dfrac{dv_p}{d\lambda}\right)$	
Heisenberg uncertainty relationships:	$\Delta x \Delta p_x \geq \dfrac{h}{4\pi}$ $\Delta E \Delta t \geq \dfrac{h}{4\pi}$ $\Delta J \Delta\theta \geq \dfrac{h}{4\pi}$	Δx, Δp_x, ΔE, Δt, ΔJ and $\Delta\theta$ are the uncertainties in the measurement of the position, momentum, energy, time, angular momentum and angular position respectively.
Time independent Schrödinger wave equation in one dimension:	$\dfrac{d^2\psi}{dx^2} + \dfrac{8\pi^2 m}{h^2}(E - V)\psi = 0$	$\psi \equiv \psi(x)$ = wave function E = total energy V = potential energy
Probability density:	$P(x,t) = \Psi^*\Psi = \lvert\Psi(x,t)\rvert^2$	
Normalization condition:	$\int_x \lvert\Psi(x,t)\rvert^2\, dx = 1$	
Schrödinger equation in operator form:	$\hat{H}\psi = E\psi$	$\hat{H}$ = Hamiltonian operator
Particle in one-dimensional potential well of infinite depth:		
a) Differential equation:	$\dfrac{d^2\psi}{dx^2} + k^2\psi = 0$ $k^2 = \dfrac{8m\pi^2 E}{h^2}$	
b) Solution:	$\psi = A\cos(kx) + B\sin(kx)$	
c) Energy eigen values:	$E = \dfrac{n^2 h^2}{8ma^2}$ $n = 1, 2, 3\ldots$	a = width of the well
d) Normalized wave function:	$\psi_n = \sqrt{\dfrac{2}{a}}\sin\left(\dfrac{n\pi}{a}x\right)$	

Principles of Quantum Computation

Quantity	Formula	Glossary
Inner product of two wave functions $\psi(x)$ and $\phi(x)$:	$\langle\psi\vert\phi\rangle = \int \psi^{*}\phi\,dx$ $\langle\phi\vert\psi\rangle = \int \phi^{*}\psi\,dx = \langle\psi\vert\phi\rangle^{*}$	
Wave function as linear combination of basis vectors:	$\vert\psi\rangle = a_1\vert\phi_1\rangle + a_2\vert\phi_2\rangle + \cdots$ $\vert\psi\rangle = \sum_{n=1}^{\infty} a_n\vert\phi_n\rangle$	$\vert\phi_1\rangle, \vert\phi_2\rangle, \ldots$ are basis vectors. $a_1, a_2, a_3, \ldots$ are complex coefficients.
Inner product of $\vert\psi\rangle$ with itself:	$\langle\psi\vert\psi\rangle = \sum_{n=1}^{\infty} \vert a_n\vert^2$	
Normalization condition:	$\langle\psi\vert\psi\rangle = 1$	
Orthogonality condition:	$\langle\psi_1\vert\psi_2\rangle = \langle\psi_2\vert\psi_1\rangle = 0$	
Condition for orthnormality of basis vectors:	$\langle\phi_1\vert\phi_2\rangle = \langle\phi_2\vert\phi_1\rangle = 0$ $\langle\phi_1\vert\phi_1\rangle = 1$ and $\langle\phi_2\vert\phi_2\rangle = 1$ In general $\langle\phi_m\vert\phi_n\rangle = \delta_{mn}$	$\delta_{mn} = \begin{cases} 0 & \text{for } m \neq n \\ 1 & \text{for } m = n \end{cases}$
Hermitian matrix $\mathbf{M}$:	$\mathbf{M}^{\dagger} = \mathbf{M}$	$\mathbf{M}^{\dagger}$ is the conjugate transpose of $\mathbf{M}$
Unitary matrix $\mathbf{U}$:	$\mathbf{U}^{\dagger}\mathbf{U} = \mathbf{U}\mathbf{U}^{\dagger} = \mathbf{I}$	
Pauli's spin matrices:	$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix},$ $\sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$	$\vert 0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ and $\vert 1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$
A qubit:	$\vert\psi\rangle = \alpha\,\vert 0\rangle + \beta\,\vert 1\rangle$	α and β are complex numbers, called the amplitude of the states.
Bloch sphere representation:	$\vert\psi\rangle =$ $\cos\frac{\theta}{2}\,\vert 0\rangle + e^{i\phi}\sin\frac{\theta}{2}\,\vert 1\rangle$	θ = polar angle ϕ = azimuth angle

Electrical Conductivity in Solids and Band Theory of Solids

Quantity	Formula	Glossary
Ohm's Law:	$V = IR$	V = voltage applied I = current flowing R = resistance A = area of cross-section L = length of the material n = carrier concentration e = electronic charge v_d = drift velocity m = mass of the electron τ =mean collision time
Resistivity:	$\rho = \frac{RA}{L}$	
Conductivity:	$\sigma = \frac{1}{\rho} = \frac{L}{RA}$	
Electric field:	$E = \frac{V}{L}$	
Current density:	$J = \frac{I}{A} = \sigma E$	
Electric current in a conductor:	$I = nev_dA$	
Drift velocity:	$v_d = \frac{eE}{m}\tau$	
Electrical conductivity of a conductor:	$\sigma = \frac{ne^2\tau}{m}$	
Mobility of electrons:	$\mu = \frac{v_d}{E} = \frac{e\tau}{m}$	
Fermi factor:	$f(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}$	E = energy level E_F = Fermi level k = Boltzmann constant T = temperature of the material
Density of states in a material in the energy range E & $E + dE$:	$g(E)dE = \frac{4\pi}{h^3}(2m)^{3/2}E^{1/2}dE$	
Number of free electrons per unit volume in the energy range E & $E + dE$:	$N(E)\,dE = g(E)f(E)\,dE$	
Total number of free electrons per unit volume in metals:	$n = \frac{8\pi}{3h^3}(2m)^{3/2}E_F^{3/2}$	m = mass of the electron

Fermi energy at 0 K:	$E_F = \frac{h^2}{8m}\left(\frac{3n}{\pi}\right)^{2/3}$	
Carrier concentration in intrinsic semiconductor:		
a) for electrons:	$n = N_C e^{-(E_C-E_F)/kT}$ $N_C = 2\left[\frac{2\pi m_e^* kT}{h^2}\right]^{3/2}$	N_C and N_V are effective density of states in the conduction and valence band. m_e^* = effective mass of electron in the material m_h^* = effective mass of hole in the material E_C = lowest energy level in the conduction band E_V = is the highest energy level in the valence band E_g = is the energy gap
b) for holes:	$p = N_V e^{-(E_F-E_V)/kT}$ $N_V = 2\left[\frac{2\pi m_h^* kT}{h^2}\right]^{3/2}$	
Fermi level in intrinsic semiconductor:	$E_F = \left(\frac{E_C+E_V}{2}\right) + \frac{3}{4}kT\ln\left(\frac{m_h^*}{m_e^*}\right)$	
a) For small kT:	$E_F = \frac{E_C+E_V}{2}$	
b) With $E_C - E_V = E_g$:	$E_F = \frac{E_g}{2} + E_V$	
Intrinsic charge carrier concentration:	$n_i = \sqrt{np} = 2\left(\frac{2\pi k}{h^2}\right)^{3/2}(m_e^* m_h^*)^{3/4} T^{3/2} e^{-E_g/2kT}$	
Conductivity of an intrinsic semiconductor:	$\sigma_i = en_i(\mu_e + \mu_h)$	μ_e = mobility of electrons μ_h = mobility of holes
Fermi energy for extrinsic semiconductors:		
a) n-type	$E_{F_n} = \frac{E_C+E_D}{2} - \frac{kT}{2}\ln\frac{N_C}{N_d}$	N_d = donor concentration
b) p-type	$E_{F_p} = \frac{E_V+E_A}{2} + \frac{kT}{2}\ln\frac{N_V}{N_a}$	N_a = acceptor concentration
Law of Mass Action:	$np = n_i^2$ = constant	

Hall voltage:	$V_H = R_H \frac{BI}{t}$	R_H = Hall coefficient B = applied magnetic field I = current flowing t = thickness of the material
Hall coefficient:		
a) For metals and n-type semiconductors:	$R_H = \frac{-1}{ne}$	
b) For p-type semiconductors:	$R_H = \frac{1}{pe}$	

Lasers

Quantity	Formula	Glossary
Boltzmann factor:	$\frac{N_2}{N_1} = e^{-h\nu/kT}$	h = Planck constant k = Boltzmann constant T = temperature ν = frequency of the electromagnetic radiation $A = A_{21}$ $B = B_{21}$ λ = wavelength
Einstein's coefficients:	$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3}$ $B_{12} = B_{21}$	
Energy density at thermal equilibrium:	$U(\nu, T) = \frac{A}{B}\frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$	
Length of the resonator cavity:	$L = n\frac{\lambda}{2}, \quad n = 1, 2, 3, \ldots$	

Optical Fibers

Quantity	Formula	Glossary
Snell's law:	$n_1 \sin\theta_1 = n_2 \sin\theta_2$	n_1 and n_2 are the refractive indices. θ_1 and θ_2 are angle of incidence & refraction. c and v are velocities of light in vacuum and the medium.
Absolute refractive index:	$n = \frac{c}{v}$	
Numerical aperture:	$\mathrm{NA} = \sin\theta_0 = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$	θ_0 = acceptance angle n_0, n_1 and n_2 are the refractive indices of surrounding medium, core and cladding.
Fraction Index Change:	$\Delta = \frac{n_1 - n_2}{n_1}$	
Relation between NA and Δ:	$\mathrm{NA} = n_1\sqrt{2\Delta}$	
V-number if surrounding medium is air:	$V = \frac{\pi d}{\lambda}\mathrm{NA}$	d = core diameter λ = wavelength of light
Number of modes for step index fiber:	$\approx \frac{V^2}{2}$	
Number of modes for graded index fiber:	$\approx \frac{V^2}{4}$	
Attenuation co-efficient (loss per unit length):	$\alpha = -\frac{10}{L}\log\left(\frac{P_{\mathrm{out}}}{P_{\mathrm{in}}}\right)$	P_{out} = output power P_{in} = input power L = length of the optical fiber

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Superconductivity

Quantity	Formula	Glossary
Critical current required to destroy the superconductivity:	$I_c = 2\pi R H_c$	R = radius of the wire H_c = critical magnetic field H_0 = minimum magnetic field required at 0 K to destroy superconductivity T_c = transition temperature
Minimum magnetic field required to destroy superconductivity at temperature T:	$H_c = H_0\left[1 - \frac{T^2}{T_c^2}\right]$	
Frequency of electromagnetic radiation emitted by a Josephson junction:	$\nu = \frac{qV}{h} = \frac{2eV}{h}$	h = Planck's constant V = voltage applied q = total charge of the pair e = electronic charge

Formulae used in lab

Quantity	Formula	Glossary
Volume resonator:	$f_x = \sqrt{\frac{(f^2 V)_{\mathrm{avg}}}{V_x}}$	f = frequency of the tuning fork V = volume of the resonating air
Young's modulus of the material of the cantilever:	$q = \frac{4mgL^3}{bd^3\delta_{\mathrm{mean}}}$	δ_{mean} = depression for mass m L, b, d = length, breadth and thickness of the cantilever

Rigidity modulus of the wire of a torsional pendulum:	$\eta = \frac{8\pi L}{R^4}\left(\frac{I}{T^2}\right)$	R = radius L = length of the wire I = moment of inertia of the attached rigid body about the axis of rotation
Moment of Inertia: (with rotation axis passing through their centers)		
a) For circular disc with radius R and mass M:	$I_1 = MR^2/2$	axis ⊥ to disc plane
	$I_2 = MR^2/4$	axis along diameter
b) For rectangular plate with length L, breadth B and mass M:	$I_3 = M(L^2+B^2)/12$	axis ⊥ to plate plane
	$I_4 = ML^2/12$	axis ⊥ to plate length
	$I_5 = MB^2/12$	axis ⊥ to plate breadth
Thickness of the paper by interference at an air wedge:	$t = \frac{\lambda L}{2\beta}$	λ = wavelength of the light L = air wedge length β = fringe width
Laser diffraction:	$\lambda = \frac{C\sin\theta_n}{n}$ $\theta_n = \tan^{-1}\left(\frac{x_n}{d}\right)$	C = grating constant n = order of diffraction x_n = distance between central and nth maxima d = distance between grating and screen
Numerical Aperture (NA):	$\sin\theta_0 = \frac{W}{\sqrt{(4L^2+W^2)}}$	L = distance from the optical fiber to screen
Capacitance and dielectric constant:	$C = \frac{\tau}{R}$ and $\epsilon_r = \frac{Cd}{\epsilon_0 A}$	τ = time constant R = resistance in series
Black box:	$R = \frac{V}{I}$ $L = \frac{V}{2\pi f I}$ $C = \frac{I}{2\pi f V}$	f = frequency of the applied AC source

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Series LCR:	$X_L = 2\pi f_0 L$ $X_C = \frac{1}{2\pi f_0 C}$ $L = \frac{1}{4\pi^2 f_0^2 C}$ $Q = f_0/\Delta f$	L = inductance C = capacitance f_0 = resonance frequency
The diode equation: (at temperature T)	$I = I_0\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$	e = electronic charge V = voltage across diode, I = current through the diode. I_0 = reverse saturation current
Wavelength of LED:	$\lambda = \frac{hc}{eV_K}$	V_K = knee voltage of the LED
Transistor parameters:	$\beta = \left[\frac{I_{C_2} - I_{C_1}}{I_{B_2} - I_{B_1}}\right]_{V_{CE}}$ $\alpha = \frac{\beta}{\beta+1}$	I_C = collector current I_B = base current V_{CE} = voltage across collector & emitter
Fermi energy of copper:	$E_F = 1.36 \times 10^{-15}\sqrt{\frac{\rho A m}{l}}$ (in J)	ρ = density of copper. A and l are area of cross-section and length of the wire. m = slope of the resistance versus temperature graph.
Linear Least Square Fit formulas:	$m = \frac{n\sum xy - \sum x \sum y}{n\sum x^2 - (\sum x)^2}$ $c = \frac{\sum y \sum x^2 - \sum x \sum xy}{n\sum x^2 - (\sum x)^2}$	n = number of data points m = slope c = y-intercept
Band gap of a thermister:	$E_g = \frac{4.606\,km}{1.6 \times 10^{-19}}$ (in eV)	k = Boltzmann constant m = slope of the log R versus $1/T$ graph

□