

## Formula Sheet for Physics 113

1 nano - meter =  $1\text{nm} = 10^{-9}\text{m}$

speed of sound at room temperature  
( $20^\circ\text{Celsius}$ ):  $343\frac{\text{m}}{\text{s}}$

permittivity constant  $\epsilon_0 = 8.85 \cdot 10^{-12} \frac{\text{C}^2}{\text{Nm}^2} = 8.85 \cdot 10^{-12} \frac{\text{F}}{\text{m}}$ , pronounced 'epsilon-naught'

permeability constant  $\mu_0 = 1.26 \cdot 10^{-6} \frac{\text{Tm}}{\text{A}} = 4\pi \cdot 10^{-7} \frac{\text{Tm}}{\text{A}}$ , pronounced 'mew-naught'

speed of light in vacuum:  $c = 3 \cdot 10^8 \frac{\text{m}}{\text{s}}$

mass of an electron:  $m_e = 0.511\text{MeV}/c^2 = 0.511 \times 10^6 \text{eV}/c^2 = 9.11 \times 10^{-31}\text{kg}$

mass of a positron = rest mass of an electron

mass of a proton:  $m_p = 1.6726 \times 10^{-27}\text{kg}$

**conversion:** different units for energy  $1\text{eV} = 1.6 \times 10^{-19}\text{J}$

Planck's constant:  $h = 6.626 \times 10^{-34}\text{Js}$

wave lengths of visible light:  $400\text{nm} - 700\text{nm}$ ,  
 $\lambda_{\text{red}} > \lambda_{\text{green}} > \lambda_{\text{blue}} > \lambda_{\text{violet}}$

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constant velocity:  $v = \frac{d}{t}$ ,  $d$ : distance,  $t$ : time

frequency:  $f = \frac{1}{T}$ , unit:  $\text{Hz} = \text{hertz} = \frac{1}{\text{s}}$

### Waves

**wave velocity:**  $v = \lambda \cdot f$ ,  $\lambda$  is the wavelength

wave speed on a string of mass  $m$  and length  $L$  under tension  $F$ :  $v = \sqrt{\frac{F}{m/L}}$

**speed of sound in air:**  $v \approx (331 + 0.6T)\frac{\text{m}}{\text{s}}$ ,

with  $T$  being the temperature in Celsius.

speed of sound in a solid bar:  $v = \frac{Y}{\rho}$  with Young's modulus  $Y$  and density  $\rho$ .

intensity  $I = \frac{\text{power}}{\text{area}}$ , power =  $\frac{\text{energy}}{\text{time}}$

**intensity level:**  $\beta = 10 \log \frac{I}{I_0}$ , threshold of

human hearing  $I_0 = 10^{-12} \frac{\text{W}}{\text{m}^2}$

Power  $P = \frac{W}{t}$ ,  $P = \frac{E}{t}$

energy of a wave:  $E \propto A^2$ ,  $A$ : amplitude

**Doppler effect:**  $f_o = f_s \frac{v \pm v_o}{v \mp v_s}$

numerator: + if the observer moves toward the source, - if the observer moves away from the source

denominator: - if the source moves toward the observer, + if the source moves away from the observer

$v_o$ : speed of observer;  $v_s$ : speed of source

### interference of waves

condition for constructive interference:  $\Delta L = 0, \lambda, 2\lambda, 3\lambda, \dots$

condition for completely destructive interference:  $\Delta L = \frac{1}{2}\lambda, \frac{3}{2}\lambda, \frac{5}{2}\lambda, \dots$

**Beat frequency:**  $f_{\text{beat}} = |f_1 - f_2|$

$f_n = n f_1$ ,  $f_1$  fundamental frequency or first harmonic,  $n = 2, 3, 4, \dots$  correspond to the higher harmonics of a string

tubes with open ends:  $f_n = \frac{v}{\lambda_n} = \frac{nv}{2L}$ , any  $n$

tubes with one closed end:  $f_n = \frac{v}{\lambda} = \frac{nv}{4L}$ ,  $n$

odd

**diffraction:** diffraction with a single slit:

$$\sin \theta = \frac{\lambda}{D}$$

circular opening:  $\sin \theta = 1.22 \frac{\lambda}{D}$

$\theta$  is the direction of the first minimum

### Light as a Wave

total energy density of an e.m. wave:  $u = \frac{1}{2} \epsilon_0 E^2 + \frac{1}{2\mu_0} B^2$

electric and magnetic field of an e.m. wave:

$$E = cB$$

intensity  $S = cu$

average (rms) values:  $E_{rms} = \frac{1}{\sqrt{2}} E_0$ ,  $B_{rms} = \frac{1}{\sqrt{2}} B_0$

### Doppler effect for electromagnetic waves:

$f_o = f_s \left( 1 \pm \frac{v_{rel}}{c} \right)$ , for  $v_{rel} \ll c$ .

The plus sign is used when source and observer move towards each other, the minus sign otherwise.

speed of light in a medium with refraction index  $n$ :  $v = \frac{c}{n}$

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wavelength of light in a medium  $\lambda_n = \frac{\lambda}{n}$

**Polarization:** Unpolarized light falls onto a polarizer:

$S = \frac{1}{2} S_0$ , with initial intensity  $S_0$

Polarized light falls on a polarizer:

$S = S_0 \cos^2 \theta$ , angle between electric field vector and polarizer axis:  $\theta$

### Double Slit Experiment

maxima (bright fringes) at:  $\sin \theta = m \frac{\lambda}{d}$ ,  $m = 0, 1, 2, \dots$ , separation of slits:  $d$

minima (dark fringes) at:

$$\sin \theta = \left( m + \frac{1}{2} \right) \frac{\lambda}{d}, \quad m = 0, 1, 2, \dots$$

**Thin-film interference:** Light reflected from the front and rear surfaces of a thin film of transparent material can interfere. A phase change of  $\lambda/2$  occurs when the light reflects at a surface where the index of refraction increases.

### Single Slit

Minima:  $\sin \theta = m \frac{\lambda}{W}$ ,  $m = 1, 2, \dots$ , slit width:  $W$

### Resolving Power - Rayleigh criterion:

Two objects can be resolved if they subtend an angle at least as large as  $\theta_{min}$ :

$\sin \theta_{min} = 1.22 \frac{\lambda}{D}$  where  $D$  is the diameter of the circular opening

reminder: angle in radians  $\theta = \frac{s}{r}$ , with arc length  $s$  and radius  $r$

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length  $s$  and radius  $r$

### Diffraction Grating

Bright fringes (principal maxima):

$\sin \theta = m \frac{\lambda}{d}$ ,  $m = 0, 1, 2, \dots$ , separation of slits:  $d$ ;

slits:  $d$ ;

line density  $N$ :  $N = 1/d$

### Relativity

time dilation:  $\Delta t = \frac{\Delta t_0}{\sqrt{1 - (v/c)^2}}$ ,  $\Delta t_0$  is a proper time interval or "proper time";  $\Delta t$  is

the time measured by an observer with relative speed  $v$ .

length contraction:

$\Delta L = \Delta L_0 \sqrt{1 - (v/c)^2}$ ,  $\Delta L_0$  is a proper length or rest length, measured by an observer in the rest frame of the object;  $\Delta L$  is the length measured by an observer with relative speed  $v$ .

relativistic momentum:  $p = \frac{mv}{\sqrt{1 - (v/c)^2}}$ ,  $m$  rest mass of an object

rest energy of an object:  $E_0 = mc^2$

total energy of an object:

$$E = \frac{m}{\sqrt{1 - (v/c)^2}} c^2 = E_0 + KE$$

**photons:** energy of a photon  $E = hf$

photoelectric effect:  $KE_{max} = hf - W_0$ ,  $W_0$ :

work function of the metal

$$\text{photon momentum: } p = \frac{E}{c} = \frac{h}{\lambda}$$

Compton effect shift in wave length:

$$\lambda' = \lambda + \frac{h}{m_{electron}c} (1 - \cos \phi)$$

de Broglie **wave length of a particle:**

$$\lambda = \frac{h}{mv} = \frac{h}{p}$$

(non-relativistic) momentum of a particle:

$$p = mv$$

**Bohr Model:**

quantization condition imposed on angular

$$\text{momentum: } L = mvr_n = n \frac{h}{2\pi}$$

radius of the  $n$ -th allowed orbit:  $r_n = \frac{n^2}{Z} r_1$

$$\text{with } r_1 = \frac{h^2}{4\pi^2 m k e^2} = 5.29 \times 10^{-11} m$$

energy of the electron in the  $n$ -th allowed orbit:

$$E_n = \frac{Z^2}{n^2} \cdot E_1, \quad \text{with } E_1 = -13.6 eV, \text{ charge of the nucleus } Z$$

lowest energy state is the ground state

line spectrum of hydrogen:

$$\frac{1}{\lambda} = R \left( \frac{1}{n'^2} - \frac{1}{n^2} \right) \quad \text{with the Rydberg constant } R = 1.0974 \times 10^7 m^{-1};$$

$n = n' + 1, n' + 2, n' + 3 \dots$   $n' = 1$  Lyman series,  $n' = 2$  Balmer series,  $n' = 3$  Paschen series

## Quantum Mechanics

Atoms are characterized by four quantum numbers:  $n, l, m_l, m_s$ .

Possible values  $l = 0, 1, \dots, n - 1$ ,

$$m_l = -l, -l + 1, \dots, 0, 1, \dots, l,$$

and  $m_s = 1/2, -1/2$ .

For hydrogen,  $E_n = \frac{1}{n^2} \cdot E_1$ , with  $E_1 = -13.6 eV$ .

Orbital angular momentum  $L = \sqrt{l(l+1)} \frac{h}{2\pi}$

Component of the angular momentum in  $z$ -

$$\text{direction: } L_z = m_l \frac{h}{2\pi}$$

**Heisenberg's Uncertainty Relation:**

$$(\Delta x)(\Delta p) \geq \frac{h}{4\pi} \quad (\Delta E)(\Delta t) \geq \frac{h}{4\pi}$$

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**Geometry:** area of a circle  $A = \pi r^2$

surface area of a sphere:  $S = 4\pi r^2$

**Logarithms:**

$$10^{\log x} = x$$

$$\text{addition: } \log a + \log b = \log(ab)$$

$$\text{subtraction: } \log a - \log b = \log\left(\frac{a}{b}\right)$$

$$\text{Quadratic equation: } ax^2 + bx + c = 0, \quad x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$\text{Vector } \vec{a}: \quad a_x = a \cos(\theta), \quad a_y = a \sin(\theta) ,$$

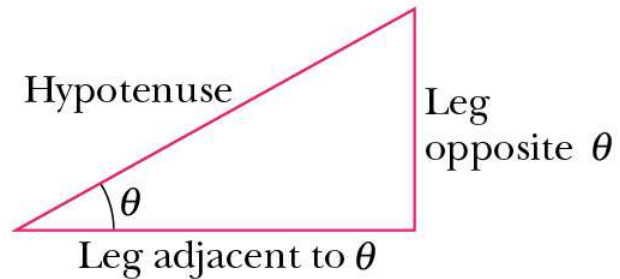
$$\tan(\theta) = \frac{a_y}{a_x}$$

Trig and right triangle:

$$\sin \theta = \frac{\text{leg opposite } \theta}{\text{hypotenuse}}$$

$$\cos \theta = \frac{\text{leg adjacent to } \theta}{\text{hypotenuse}}$$

$$\tan \theta = \frac{\text{leg opposite } \theta}{\text{leg adjacent to } \theta}$$



**Units:** On this page of the formula sheet, you will find relations between units. The table contains only **SI - units**.

Note that once in a while, the same letter might either be the symbol for a physical quantity or the abbreviation for a unit, e.g.  $C$  may stand for capacitance, or for "Coulomb". This should always be clear from the context. If it is not clear to you, ask! Non SI-unit: the electron-volt,  $eV$ , is a unit for energy often used for elementary particles.  $1eV = 1.6 \cdot 10^{-19} J$ .

physical quantity	symbol	unit	abbreviation for unit
force	$\vec{F}$	Newton	$N = \frac{kgm}{s^2}$
electric charge	$Q$	Coulomb	$C$
electric field	$\vec{E}$	Newton/Coulomb	$\frac{N}{C} = \frac{V}{m}$
magnetic field	$\vec{B}$	Tesla	$1T = \frac{N}{Am}$
electric potential, voltage	$V$	Volt	$V$
energy, work	$E, PE, KE, W$	Joule	$J = Nm$
power	$P$	Watt	$W = \frac{J}{s} = VA = \frac{VC}{S}$
frequency	$f$	Hertz	$Hz = \frac{1}{s}$
intensity	$I, S$	Watt/meter <sup>2</sup>	$\frac{W}{m^2}$
sound intensity level	$\beta$	decibels	$dB$