What is TEM?

stands for Transmission Electron (Microscope/Microscopy)

Q: Why use electrons instead of light for imaging nanomaterials?

A: 1) Shorter wavelength (λ)
$\Rightarrow$ Higher resolution

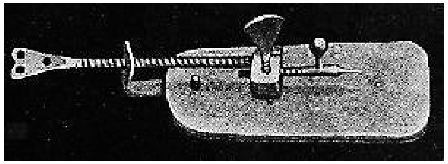
2) Wavelength determined by voltage
$\Rightarrow$ Variable & (nearly) monochromatic

3) Small probe sizes
$\Rightarrow$ Study extremely small volumes/isolated phases

4) Interaction with core electrons
$\Rightarrow$ Chemical sensitivity/detection

Brief History of Microscopy & Diffraction (I)

van Leeuwenhoek, Hooke (1670s)
⇒ 1st simple optical microscopes

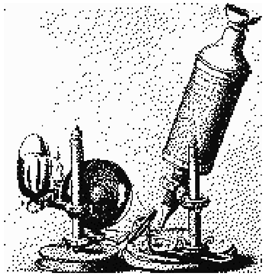


van Leeuwenhoek's microscope

Antony van Leeuwenhoek

Airy, Rayleigh, Abbe (mid-late 1800s)
⇒ Resolution of optical microscopes ~λ

Lord Rayleigh (John William Strutt)



Hooke's microscope

J. J. Thomson (ca. 1905)
⇒ Discovered electron, measured *e/m*

Joseph John Thomson

von Laue, Braggs (ca. 1914)
⇒ Discovered/explained x-ray diffraction

Max von Laue

Brief History of Microscopy & Diffraction (II)

de Broglie (1920s)
⇒ Proposed matter waves (wave/particle duality)

Prince Louis-Victor Pierre Raymond de Broglie

G. P. Thomson, Davisson & Germer (1920s)
⇒ Observed electron diffraction

Ernst Ruska

Bethe (1920s)
⇒ Theory of dynamical electron diffraction

Busch, Ruska, Knoll, Rudenberg (1930s)
⇒ Short, current-carrying coil acts as an electron lens
and produced 1st electron microscope images

J. Cowley, A. Howie, J. C. H. Spence, K. Tanaka,
P. B. Hirsch, J.Gjønnes (1970s and later)
⇒ Modern electron microscopy techniques and theory

John Cowley and Sumio Iijima

Electron Microscopy Facilities

National Labs:
Argonne National Laboratory, Electron Microscopy Center
http://www.anl.gov/cnm/group/electron-microscopy-center /

Brookhaven National Laboratory, Center for Functional Nanomaterials
https://www.bnl.gov/cfn/facilities/microscopy.php

Lawrence Berkeley National Laboratory, National Center for Electron Microscopy
http://foundry.lbl.gov/facilities/ncem/

Universities:
Arizona State University, John M. Cowley Center for High Resolution Electron Microscopy
https://asu.corefacilities.org/service_center/show_external/3195/
john-m-cowley-center-for-high-resolution-electron-microscopy-chrem

Lehigh University, Center for Advanced Materials and Nanotechnology
http://www.lehigh.edu/nano/emf_facility.html

University of Colorado, Boulder Laboratory for 3-D Electron Microscopy of Cells
http://bio3d.colorado.edu/

TEM Models for Materials Science:

Hitachi HF-3300

http://www.hitachi-hta.com/

FEI Titan Themis^3 300

http://www.fei.com/

Zeiss Libra 200FE-EFTEM

http://www.smt.zeiss.com/

JEOL JEM-ARM200F

http://www.jeol.com/

Evolution of Commercial TEMs

Permanent magnet TEM

Analog controls
Film plates

Digital controls
Digital camera
High vacuum
High voltage

Imaging and Presentation Software

Product	Acquiring & Measuring	Processing	Annotating
Digital Micrograph^	√	√	√
ImageJ*	√	√	
Photoshop/GIMP#		√	√
Illustrator/Inkscape◊			√

<u>free downloads:</u>
^http://www.gatan.com/resources/scripting/demo/index.php
*http://rsb.info.nih.gov/ij/
#http://www.gimp.org/
◊http://www.inkscape.org

Higher Voltage/Energy

Advantages	Disadvantages
higher resolution (wavelength)	lower resolution (interaction volume)
less image distortion (aberrations)	more expensive
greater penetration (thick specimen)	lower contrast
brighter beam	bigger/taller column
shorter wavelength (diffraction)	shorter wavelength (dark-field)
less beam damage	more unwanted radiation
	higher vacuum needed

Note: Increasing voltage beyond ~200 KV does not significantly increase resolution.

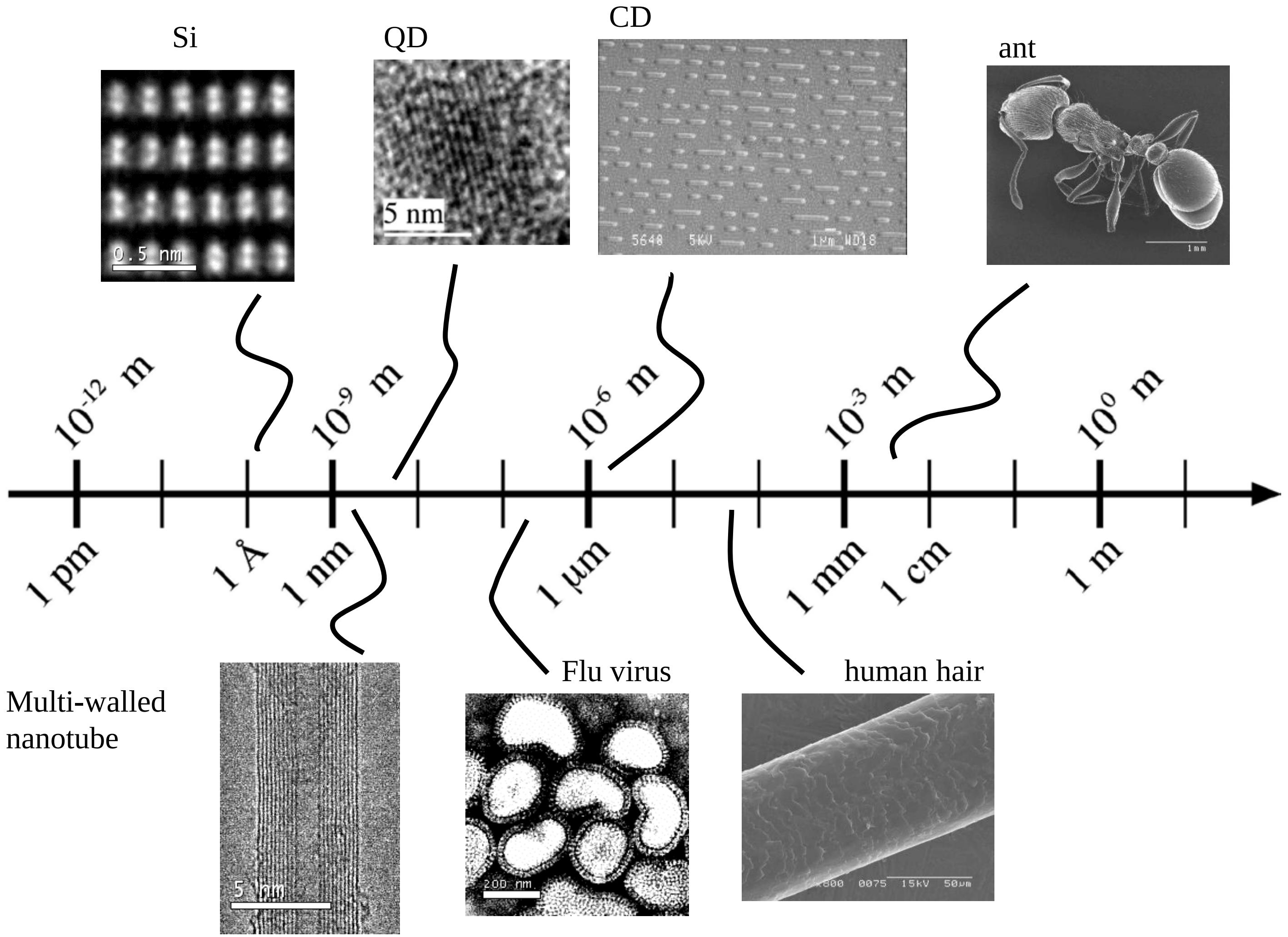
Higher Voltage TEMs

HVEM: High-Voltage Electron Microscope (1-3 MV)

IVEM: Intermediate-Voltage Electron Microscope (200-400 KV)

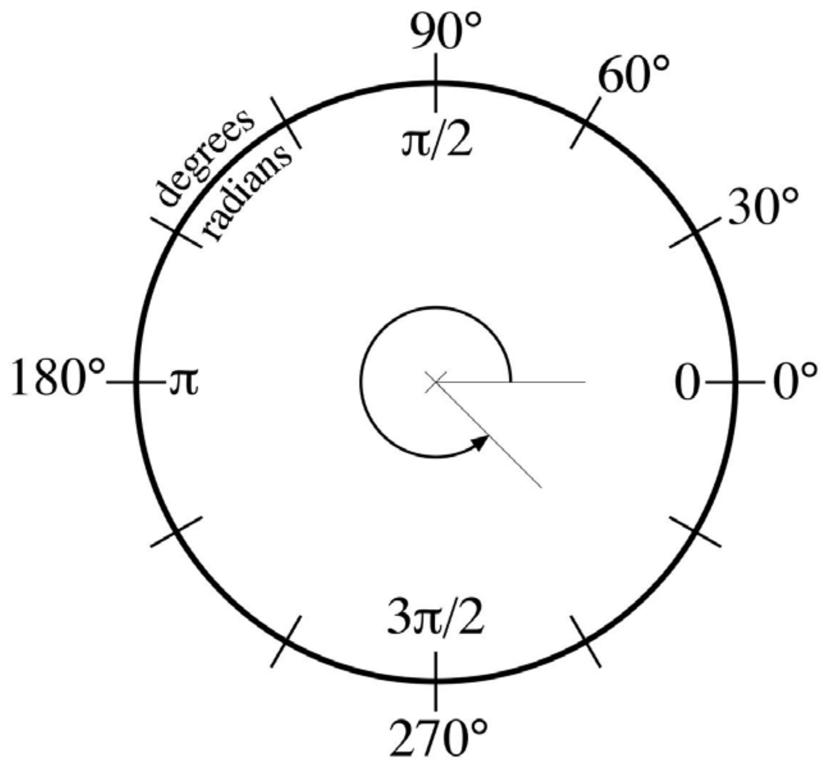
SDSM&T → JEOL JEM-2100 TEM: 200 KV

Units: *Length*



Units: *Angle*

Degrees: ° or deg
Radians: rad (dimensionless)



$$\angle \text{rad} = \frac{\text{arc length}}{\text{radius}}$$

$$\pi = 3.14159...$$

$$360° = 2\pi \ \text{rad}$$

Conversion:

$$1 = \frac{180°}{\pi \ \text{rad}} = 57.3 \ \frac{\text{deg}}{\text{rad}}$$

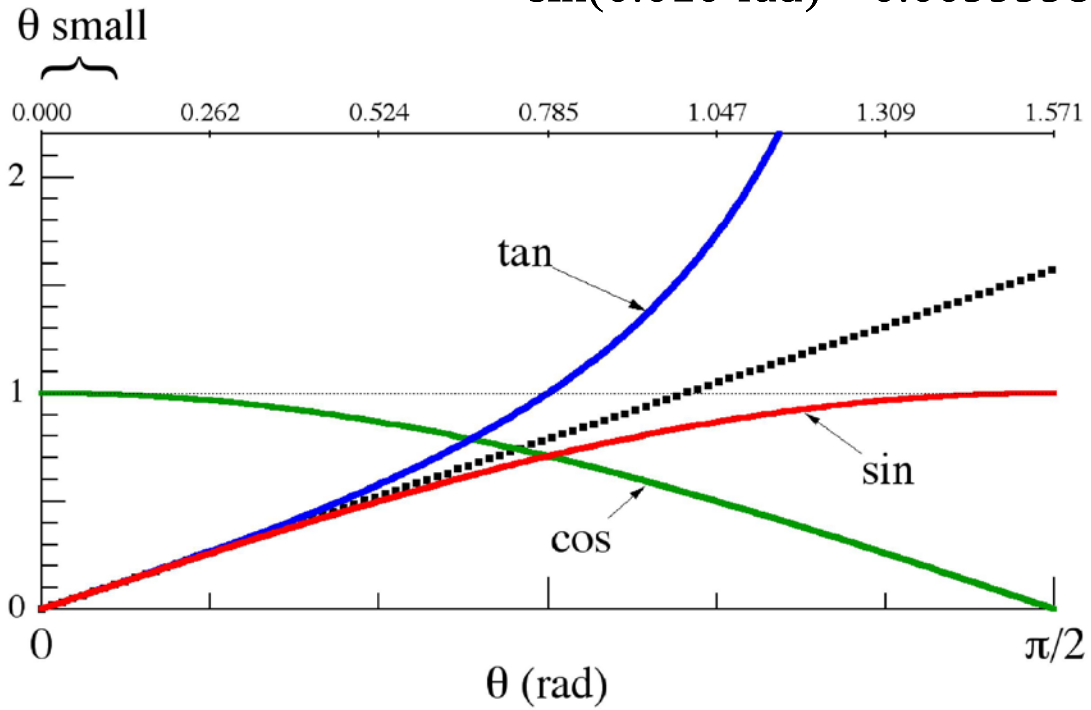
Small-Angle Approximation

$$\sin\theta \approx \theta \ \ (\text{in rad}) \qquad \cos\theta \approx 1 \qquad \tan\theta = \frac{\sin\theta}{\cos\theta} \approx \theta \ \ (\text{in rad})$$

"Typical" small angle:

$$0.5° = 0.0087 \text{ rad} \approx 10 \text{ mrad}$$

$$\sin(0.010 \text{ rad}) = 0.0099998...$$



Physical Constants

quantity	symbol	value
elementary charge	e	$e = 1.60 \text{ x } 10^{-19}$ C
speed of light	c	$c = 3.00 \times 10^{8}$ m/s
Planck's constant	h	$h = 6.63 \times 10^{-34}$ J·s
electron rest mass	m_0	$m_0 = 9.11 \times 10^{-31}$ kg

More Physical Units

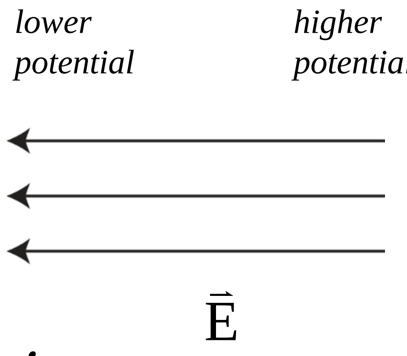
unit	symbol	definition
newton	N	1 N=1 kg·m/s^2
joule	J	1 J = 1 N·m
volt	V	1 V = 1 J/C
ampere	A	1 A = 1 C/s
electron volt	eV	1 eV = 1.602 $\times$ 10^{-19} J

Shortcuts to physical constants:

hc = 1240 eV · nm=1.24 KeV · nm

m_0c^2=511 KeV

Electric Potential



Electric Field: $$\vec{E} = -\vec{\nabla}\Phi$$

In 1-D: $$E_z = -\frac{d\Phi}{dz}$$

Electric Potential: $$\Phi(z) = \Phi(0) - \int_{z'=0}^{z} \varepsilon_z \cdot dz'$$

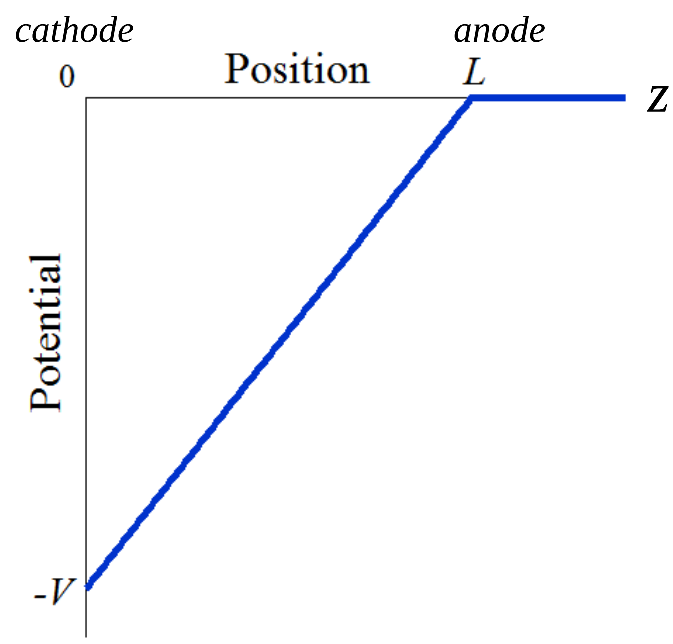
Pick: $\Phi(L) = 0$ (ground)

Define: $\Phi(0) = -V$

Simple Case: uniform field

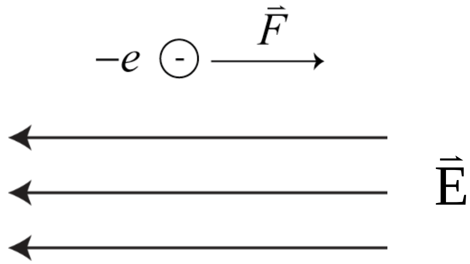
$$E_z = -\frac{V}{L}$$

$$\Phi(z) = -V \cdot \left(1 - \frac{z}{L}\right)$$



Potential Energy

Force: $\vec{F} = q\vec{\mathrm{E}}$ $\qquad q = -e$



Electron, 1-D: $F_z = -e \cdot \left(-\frac{V}{L} \right) = \frac{eV}{L}$

Work done: $W = -\int \vec{F} \cdot d\vec{r} = -\int_{z'=L}^{0} F_z \cdot dz' = eV$

Potential Energy:

$W = U(0) - U(L)$

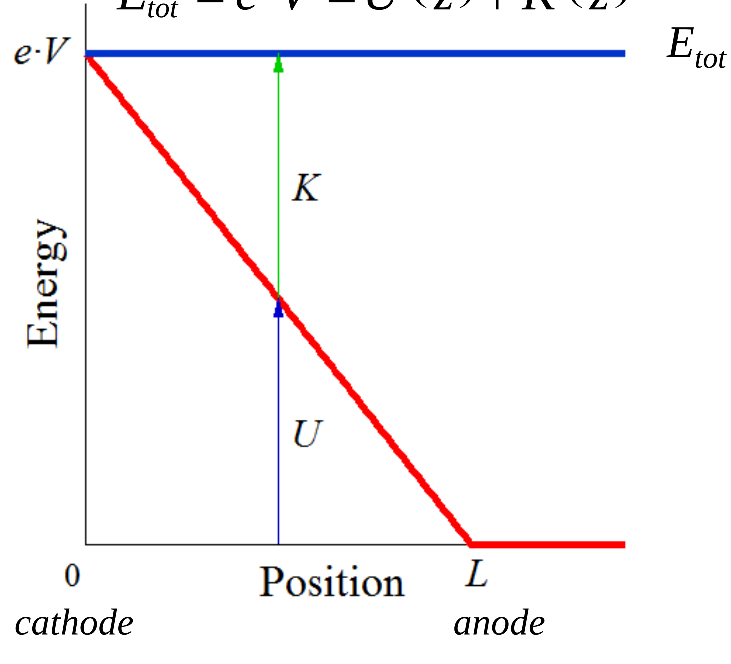
$U(L) = 0 \;\; (\text{ground})$

$\Rightarrow U(0) = eV$

Total energy conserved.

$U(0) \rightarrow K(L)$

$E_{tot} = e \cdot V = U(z) + K(z)$



De Broglie Wavelength

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

//momentum

particle property

wave property

Electron Wavelength (I)

$$mc^2 = E + m_0c^2$$

relativistic mass ↑ kinetic energy ↑ rest mass ↑

//relativistic mass-energy

$$m = \gamma m_0$$

$$\gamma = 1 \Big/ \sqrt{1-(v/c)^2}$$

$$mc^2 = \sqrt{\left(m_0c^2\right)^2 + \left(pc\right)^2}$$

← momentum

//from relativity

$$\lambda = \frac{h}{p} = \frac{hc}{pc} = \frac{hc}{\sqrt{(E+m_0c^2)^2 - (m_0c^2)^2}}$$

$$\boxed{\lambda = \frac{hc}{\sqrt{E\cdot\left(E+2m_0c^2\right)}}}$$

//wavelength

Non-Relativistic Electron Wavelength

If

$$E << 2m_0c^2$$

$$E + 2m_0c^2 \approx 2m_0c^2$$

$$\lambda \approx \frac{hc}{\sqrt{E\cdot\left(2m_0c^2\right)}} = \frac{h}{\sqrt{2m_0E}} = \lambda_{nr}$$

Use relativistic form in this class!

Comparison

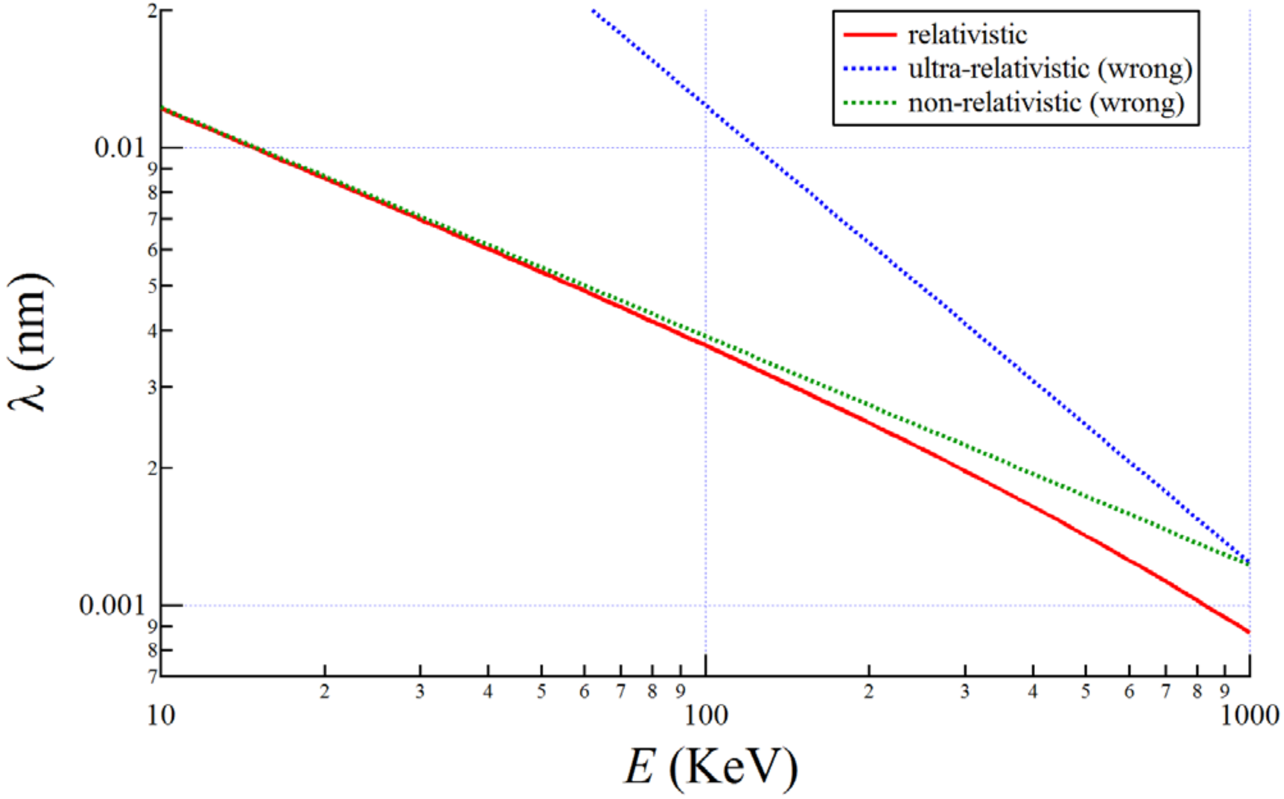
Rewrite: $$\lambda = \frac{\lambda_{nr}}{\sqrt{1+\left(\frac{E}{2m_0c^2}\right)}}$$ $\left(\text{Note: } \lambda < \lambda_{nr}\right)$

Or:

where: $$E_{nr} \equiv \left(\frac{m+m_0}{2m}\right)\cdot E$$ //sometimes useful

Note: It always holds that $m \geq m_0$ $E_{nr} \leq E$

Wavelength vs. Energy



$$\lambda = \frac{hc}{\sqrt{E \cdot \left(E + 2m_0c^2\right)}}$$ //relativistic

$$\lambda = \frac{hc}{E}$$ //ultra-relativistic (i.e., light)

$$\lambda = \frac{h}{\sqrt{2mE}}$$ //non-relativistic

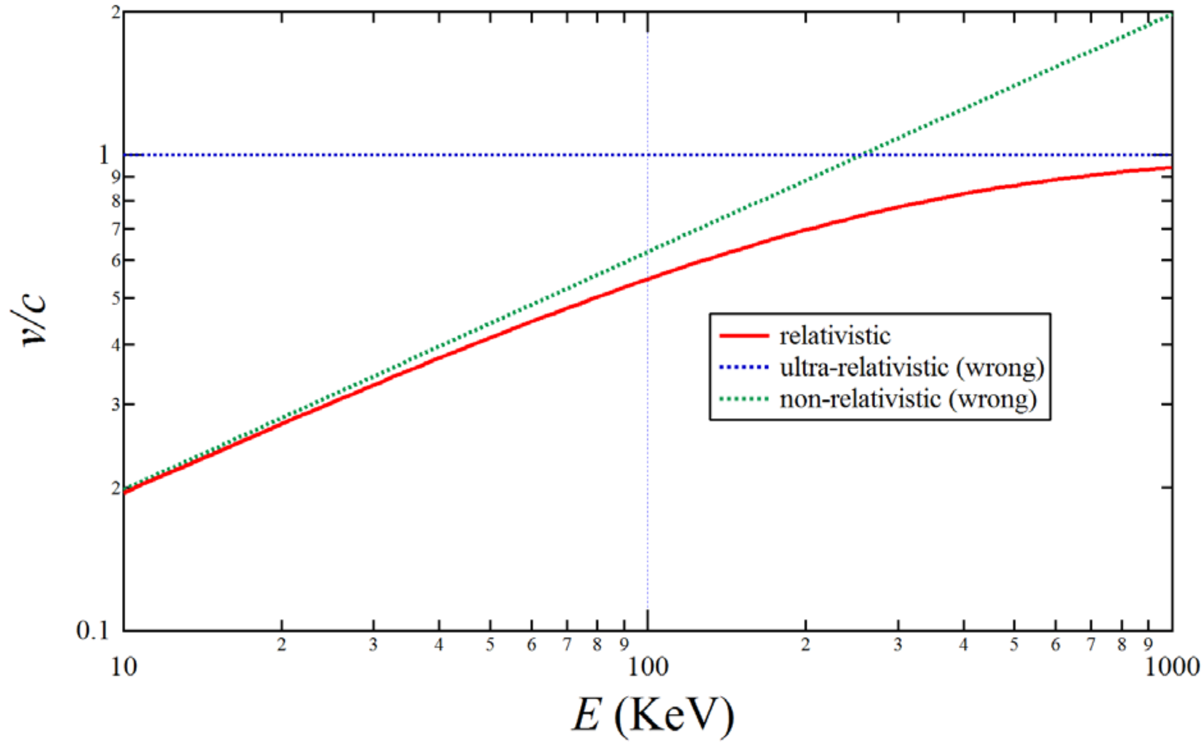
Find Velocity

$$p = mv$$

$$\frac{v}{c} = \sqrt{1 - \frac{1}{\left(1 + \frac{E}{m_0 c^2}\right)^2}}$$

If $E << 2m_0c^2$ $$\frac{v}{c} \approx \frac{v_{nr}}{c} = \sqrt{\frac{2E}{m_0 c^2}}$$ //non-relativistic

Velocity vs. Energy



$$v/c = \sqrt{1 - \frac{1}{\left(1 + E/m_0 c^2\right)^2}}$$ //relativistic

$$v/c = 1$$ //ultra-relativistic (i.e., light)

$$v/c = \sqrt{\frac{2E}{m_0 c^2}}$$ //non-relativistic

Group vs. Phase Velocity

$$\lambda = \frac{hc}{\sqrt{E \cdot \left(E + 2m_0c^2\right)}} = \frac{hc}{\sqrt{E_{tot}{}^2 - \left(m_0c^2\right)^2}}$$

$$E + m_0c^2 = hf$$ //photoelectric effect

$$f = \frac{E + m_0c^2}{h}$$ //frequency

$$v_p = \lambda f = \frac{1}{\sqrt{1 - \left(\frac{m_0c^2}{E + m_0c^2}\right)^2}} \cdot c$$ //phase velocity

$$v_p/c = \frac{1}{\sqrt{1 - \frac{1}{\left(1 + E/m_0c^2\right)^2}}} = \frac{c}{v}$$

v ← group velocity

$$v_p > c!$$