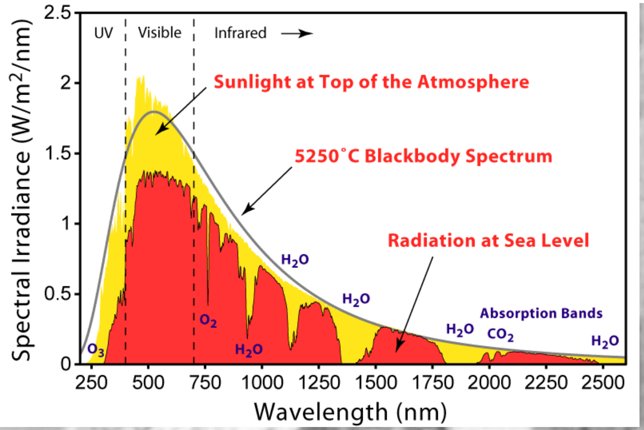
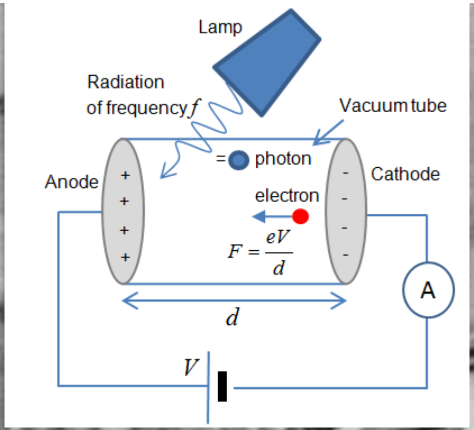
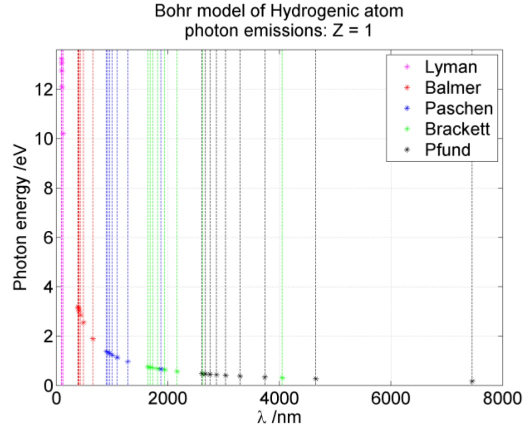
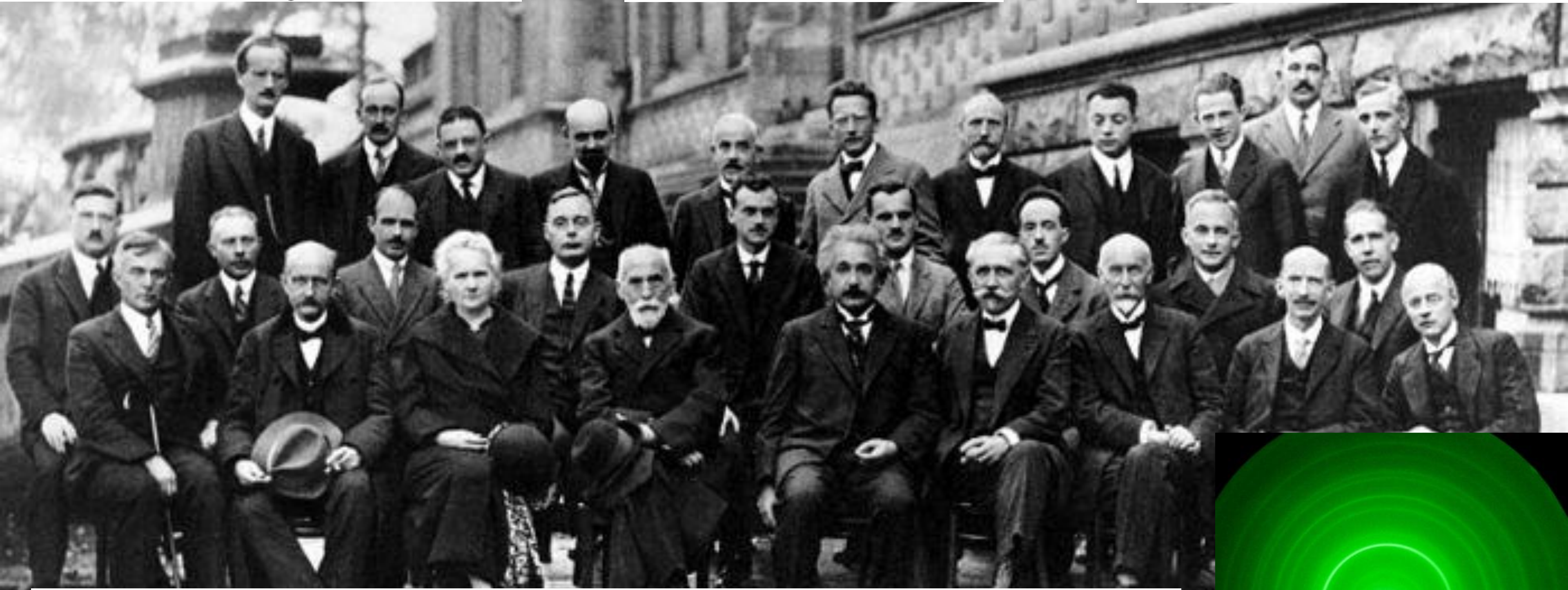
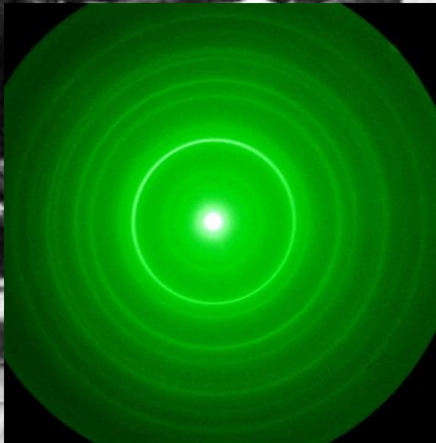










A history of Quantum Theory

Dr Andrew French

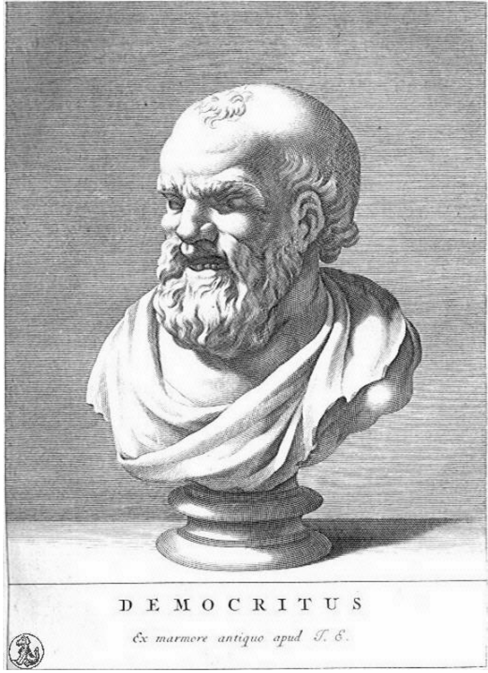
In ancient Greece, Democritus* proposed that matter is composed of ‘uncuttable’ *atomon* components. Today we call them **atoms**.

Unfortunately this idea only became scientific orthodoxy in the twentieth century!

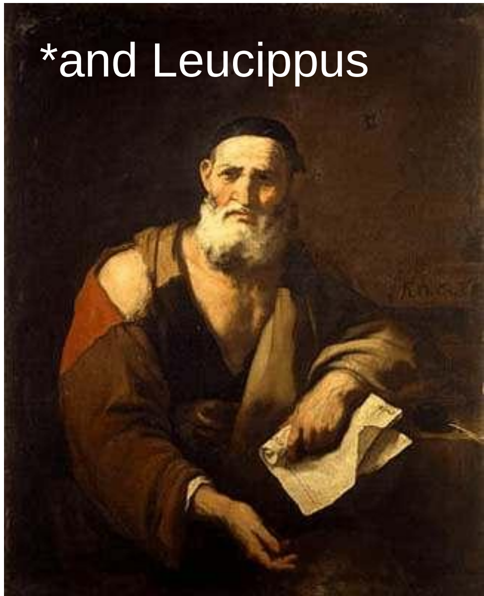
In the Standard Model of modern Physics, atoms are themselves composed of **fundamental particles**. **Quarks** are ‘glued’ together to form the **protons** and **neutrons** which comprise a tiny positively charged **atomic nucleus**, with radius 10^{-15}m (1femto-metre, fm). Around them is a cloud of negatively charged **electrons**. So what are these particles, and how do they interact?

Four key experiments at the turn of the twentieth century showed that the laws of Physics at these small scales are quite different, and much stranger, than the Classical theories of Newton, Maxwell etc.

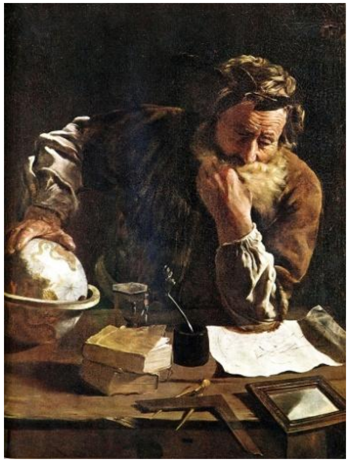
This theory is called **Quantum Mechanics**



Democritus
460 BC – 370BC

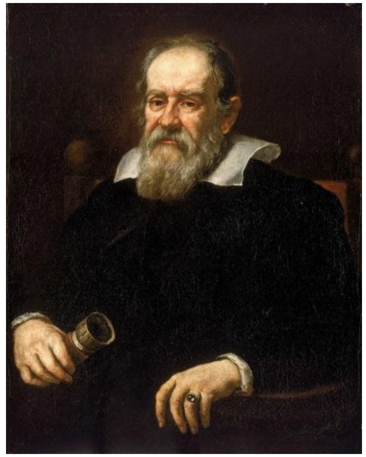


Mechanics



Archimedes
287BC - 212BC

Mechanics



Galileo Galilei
1564-1642

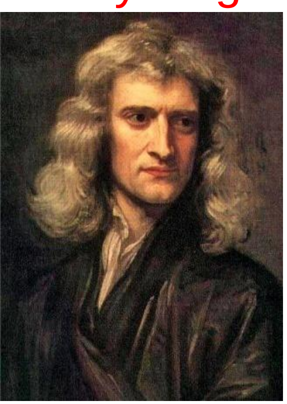
Orbits

Johannes Kepler
1571-1630

Waves

Christiaan Huygens
1629 - 1695

Everything!

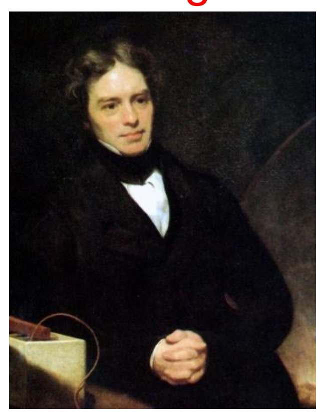


Isaac Newton
1642-1726

Waves, heat

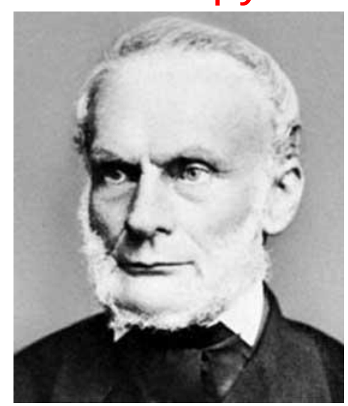
Joseph Fourier
1768-1830

Electromagnetism



Michael Faraday
1791-1867

Entropy



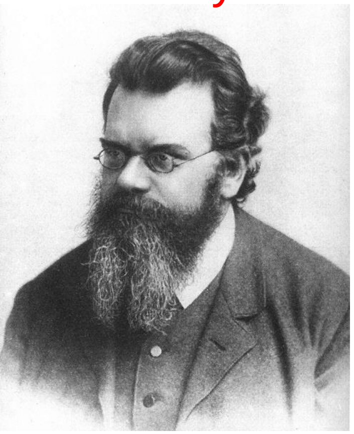
Rudolf Clausius
1822-1888

Electromagnetism

James Clerk
Maxwell
1831-1879

A small selection of the **Pioneers of Classical Physics**

Thermodynamics

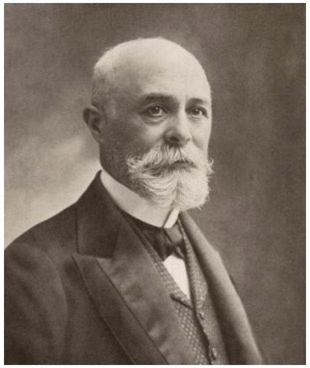


Ludwig Boltzmann
1844-1906

X-Rays

Wilhelm Röntgen
1845-1923

Radioactivity



Antoine Henri
Becquerel
1852-1908

Electron

J.J.Thompson
1856-1940

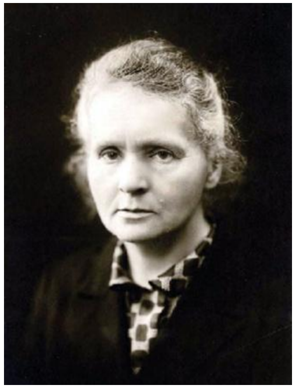
Radio waves

Heinrich Hertz
1857-1894

Quanta

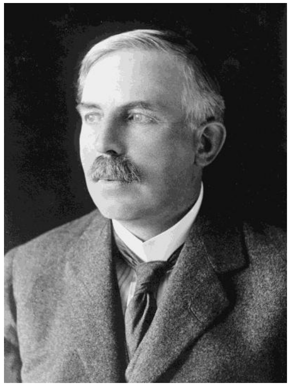
Max Planck
1858 – 1947

Radioactivity



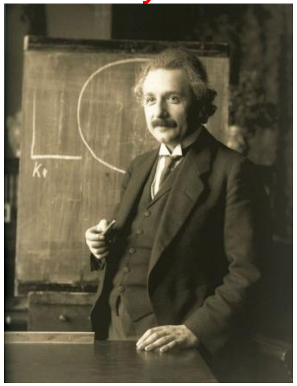
Marie Curie
1867-1934

Atomic nucleus



Ernest Rutherford
1871-1937

Quantum Theory
Relativity



Albert Einstein
1879-1955

Quantum
atom

Niels Bohr
1885-1962

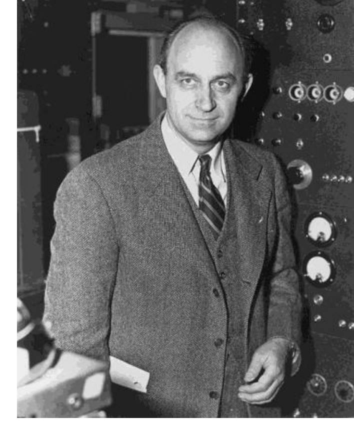
A small selection of the **Pioneers of Atomic & Quantum Physics**

Max Born
1882 –1970

Erwin Schrödinger
1887 –1961

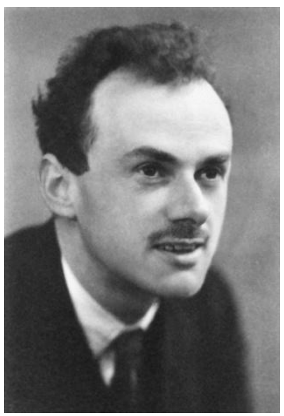
Louis de Broglie
1892 –1987

Wolfgang Pauli
1900 –1958



Enrico Fermi
1901-1954

Werner
Heisenberg
1901 – 1976



Paul
Dirac
1902-1984

George
Gamow
1904-1968

Richard
Feynman
1918-1988

Murray
Gell-Mann
1929-

Peter Higgs
1929-

A small selection of the **Pioneers of modern Quantum Physics**

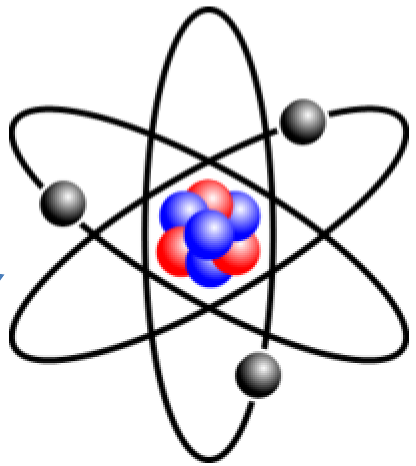
The development of Quantum Mechanics was a truly collaborative effort, and unprecedented in terms of the speed at which the theory was assembled.
The 1927 Solvay Conference in Brussels was devoted to Quantum Theory.
Many of the pioneers of the subject attended. Nine were eventually Nobel laureates.

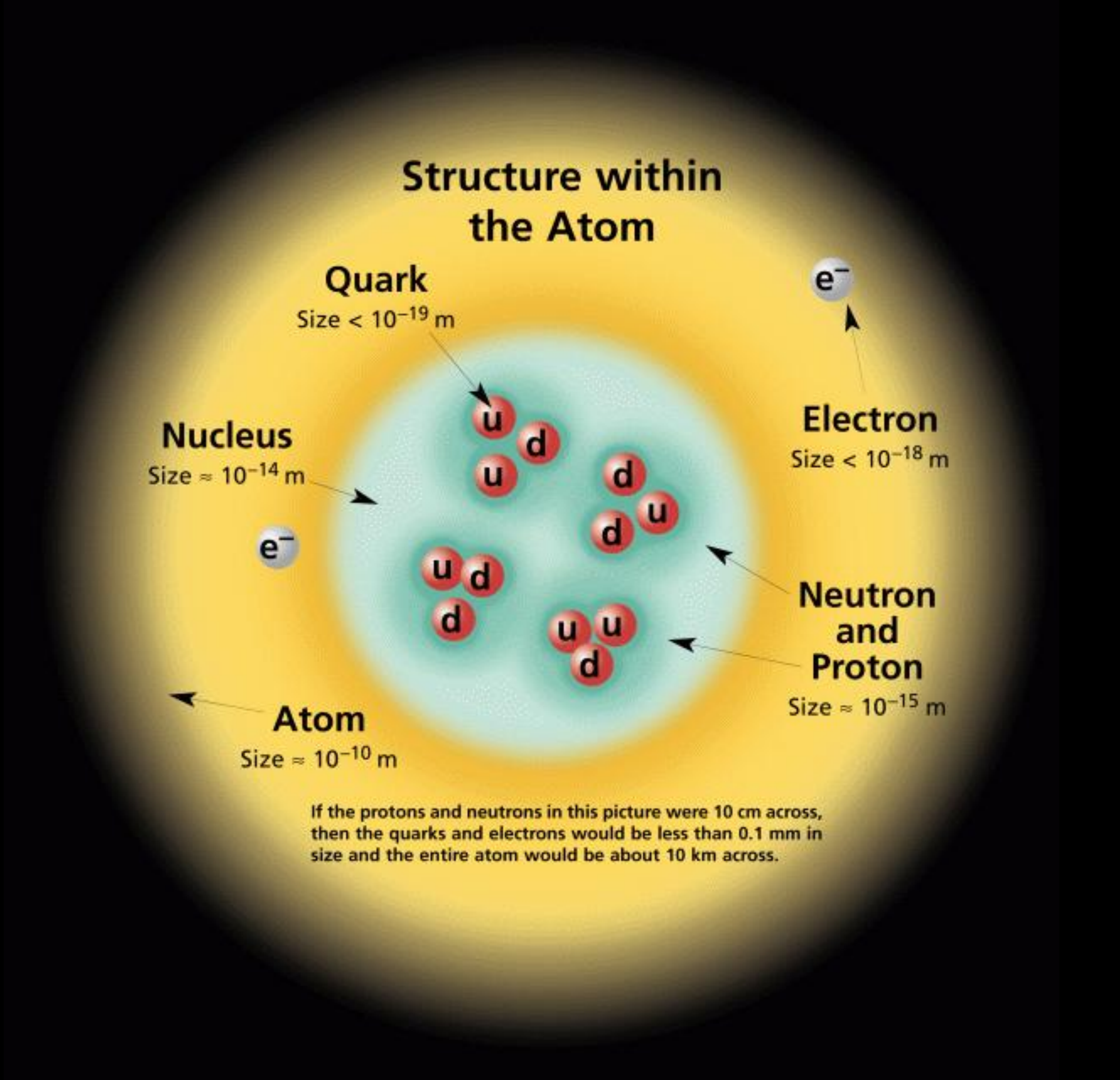
But first we must start with

ATOMS

and why they exist at all

This model has
a serious flaw!

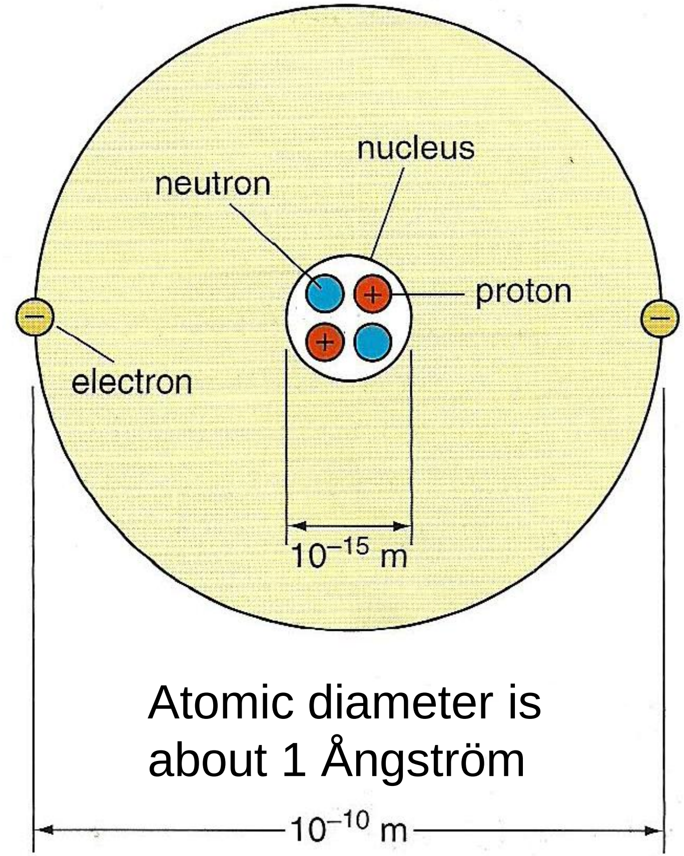



Structure within the Atom
Quark
Size < 10^{-19} m
Nucleus
Size ≈ 10^{-14} m
Electron
Size < 10^{-18} m
e^-
e^-
u
d
u
d
u
d
u
d
d
u
u
d
Neutron and Proton
Size ≈ 10^{-15} m
Atom
Size ≈ 10^{-10} m
If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

The size of an atom

Earth diameter = 12,756km

Marble diameter = 3.6cm



Atomic diameter is about 1 Ångström

$$\left(\frac{1.2756\times10^{7}}{3.6\times10^{-2}}\right)^{3}\approx4.4\times10^{25}$$

Volume of Earth in marbles

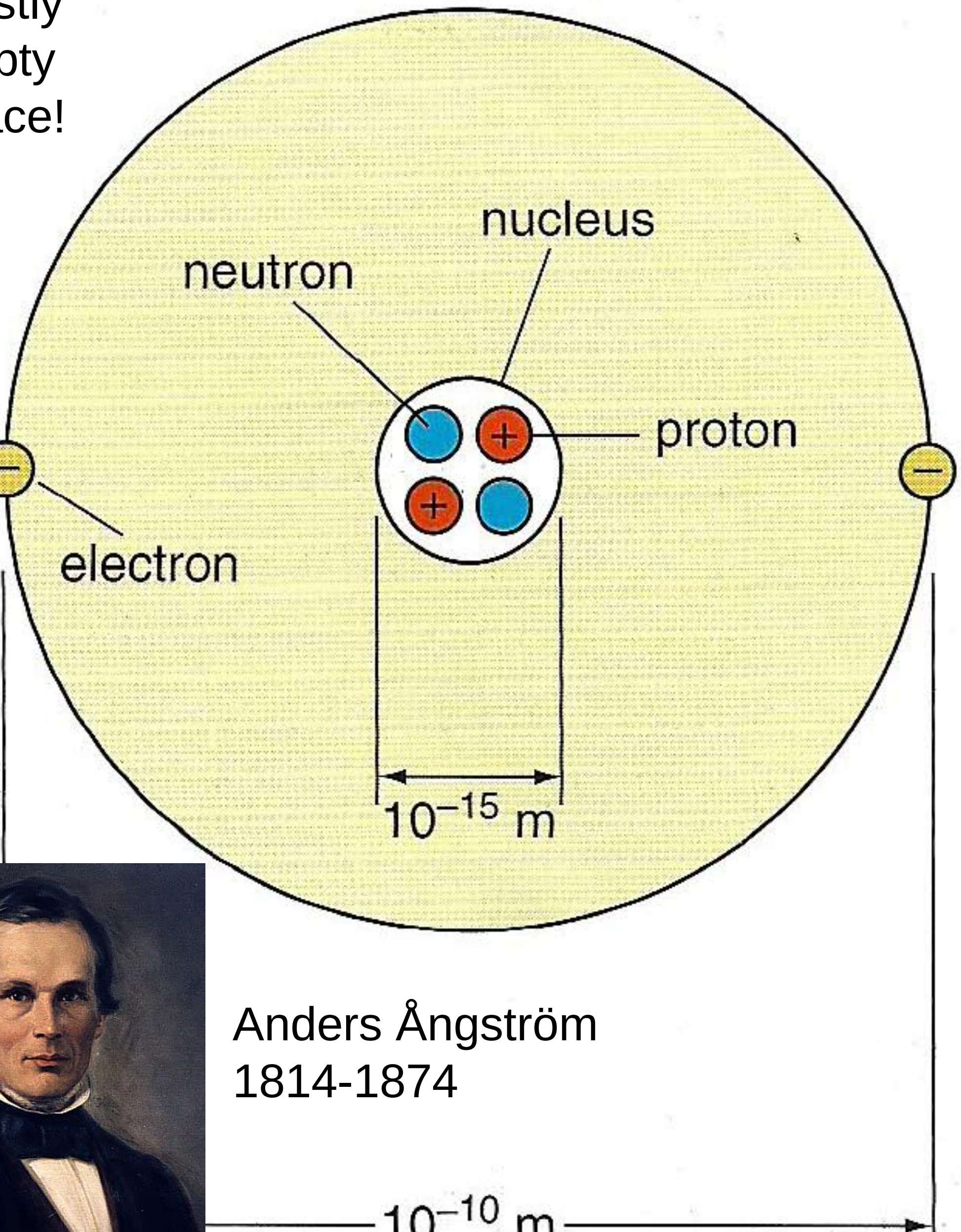
$$\left(\frac{3.6\times10^{-2}}{1\times10^{-10}}\right)^{3}\approx4.7\times10^{25}$$

Number of atoms in a marble

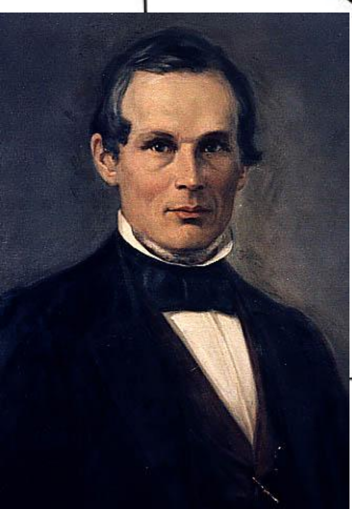
There are as many atoms in a marble as an Earth made of marbles!

Atomic mass and density

Mostly empty space!



This is one Ångström



Anders Ångström
1814-1874

$$m_e = 9.109 \times 10^{-31}\,\mathrm{kg}$$

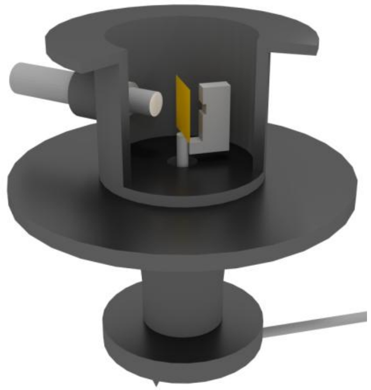
$$m_p = 1.673 \times 10^{-27}\,\mathrm{kg}$$

$$m_n = 1.675 \times 10^{-27}\,\mathrm{kg}$$

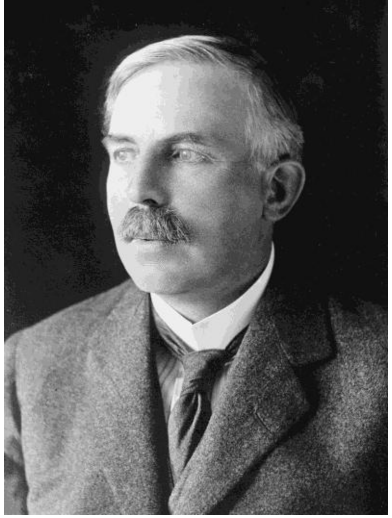
$$\rho \approx \frac{1.673 \times 10^{-27}\,\mathrm{kg}}{\frac{4}{3}\pi \times \left(\frac{1}{2} \times 10^{-10}\right)^3}$$

$$\rho \approx 3{,}200\,\mathrm{kgm}^{-3}$$

$$\rho_{water} \approx 1{,}000\,\mathrm{kgm}^{-3}$$

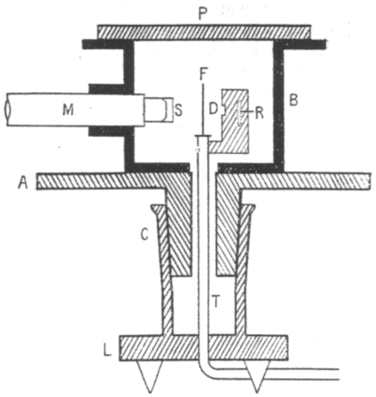


Ernest
Rutherford
1871-1937



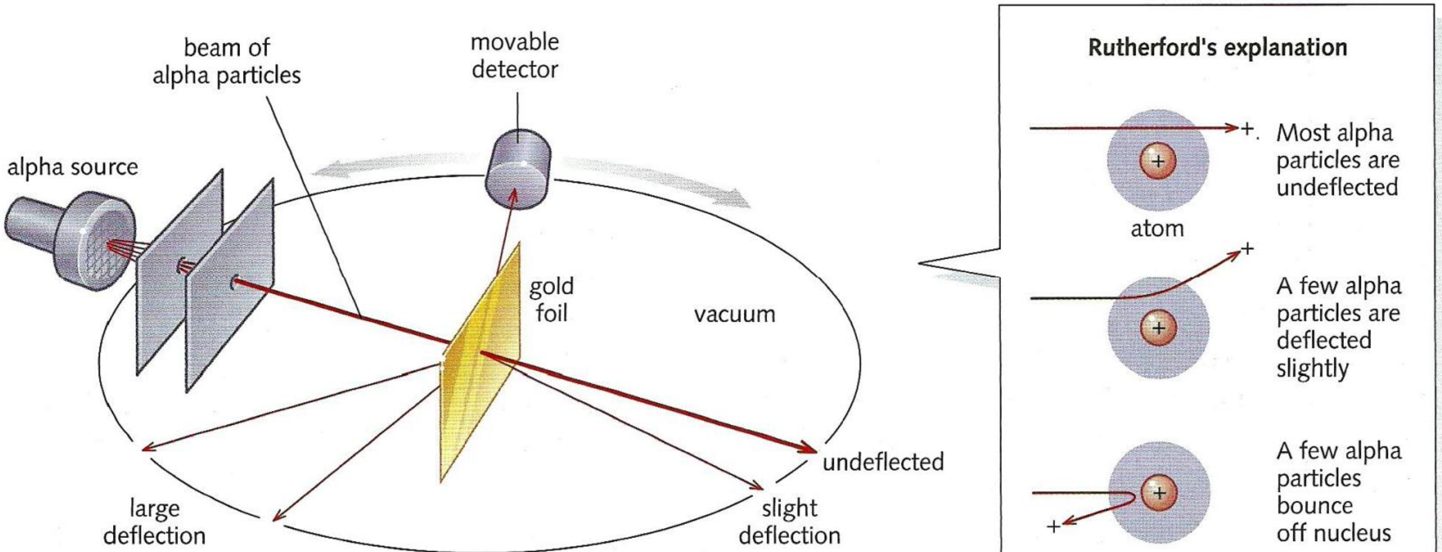
Hans
Geiger

Ernest
Marsden



The **Rutherford scattering experiment** , performed 1908-1913 at the University of Manchester, provided convincing evidence for the modern nuclear model of **atoms**

alpha particle
is a helium nucleus



But there is a *major problem here*. For electrons to 'orbit' a nucleus, they must be **accelerating**. Electromagnetism tells us that accelerating charges **radiate**.

A Classical calculation tells us that electrons should only exist for about 10^{-10}s!

$$\dot{E} = \frac{dE}{dt} = -\frac{e^2}{6\pi\varepsilon_0 c^3} a^2$$

Radiated power

$$\tau = \frac{\frac{1}{2} m_e v^2}{\left|\dot{E}\right|}$$

'electron lifetime'

$$\dot{E} = -\frac{e^2}{6\pi\varepsilon_0 c^3} \times \left(\frac{Ze^2}{4\pi\varepsilon_0 m_e r^2} \right)^2$$

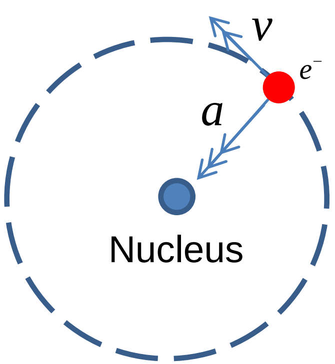
$$\therefore \dot{E} = -\frac{Z^2 e^6}{96\pi^3 \varepsilon_0^3 c^3 m_e^2 r^4}$$

$$\tau = \frac{Ze^2}{8\pi\varepsilon_0 r} \times \frac{96\pi^3 \varepsilon_0^3 c^3 m_e^2 r^4}{Z^2 e^6}$$

$$\tau = \frac{12\pi^2 \varepsilon_0^2 c^3 m_e^2 r^3}{Ze^4}$$

$$\tau \approx \boxed{4.7 \times 10^{-11}\,\mathrm{s}}$$

$$\varepsilon_0 = 8.854187817 \times 10^{-12}\,\mathrm{Fm^{-1}}$$
$$e = 1.6021766208(98) \times 10^{-19}\,\mathrm{C}$$
$$c = 2.99792458 \times 10^{8}\,\mathrm{ms^{-1}}$$
$$m_e = 9.10938356(11) \times 10^{-31}\,\mathrm{kg}$$



So how do atoms exist?

To answer the question “why do atoms exist?” we will need models which were developed to explain three perplexing problems of Classical Physics

1. **The spectrum of radiation from a hot body**
2. **The photoelectric effect**
3. **The spectral lines of Hydrogen**

The implications of these models are *profound*:

- All **particles** have an associated **wave-like character**
- These waves can interfere, diffract, tunnel through barriers
- The wave-pattern is related to the **probability** of finding a particle
- ***Uncertainty*** appears to be built into Physics

BLACK BODY RADIATION

Radiation power per square metre

$$I = \varepsilon \sigma T^4$$

Absolute temperature /K

Emmisivity

Stefan-Boltzmann constant

$$\sigma = 5.67 \times 10^{-8}\,\mathrm{Wm^{-2}K^{-1}}$$

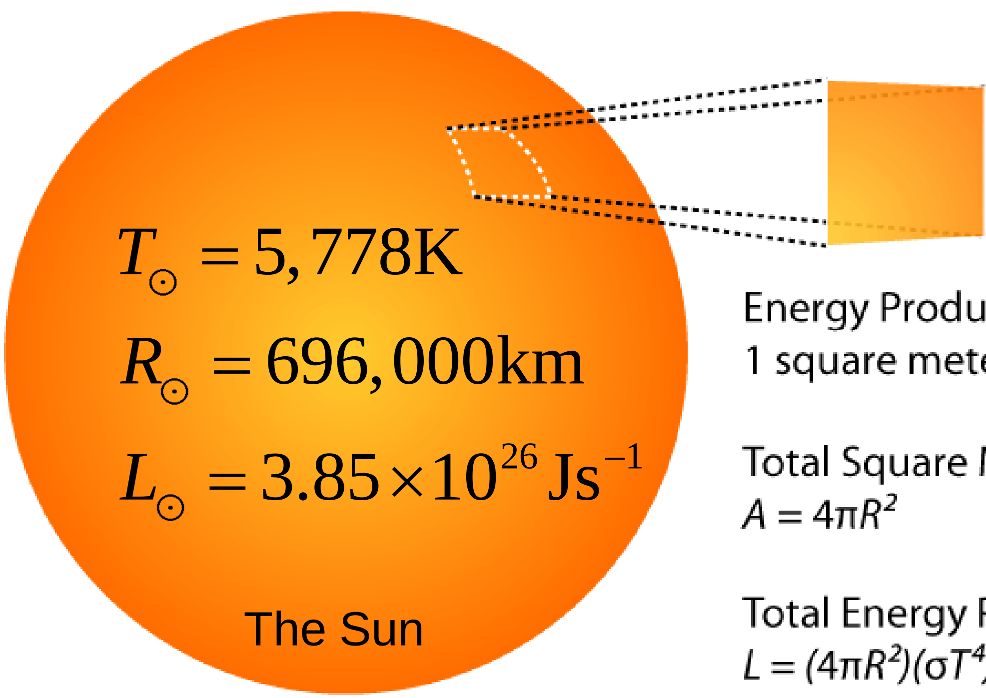
$$\varepsilon = 1$$

A ‘**Black Body**’. i.e. all incident radiation is absorbed and then re-radiated

For a ‘Black Body’ at 20^{o}C = 293K

$$\boxed{I = 418\,\mathrm{Wm^{-2}}}$$

It is interesting to compare this to the maximum solar energy incident upon the Earth, which is on average about 1,361 $\mathrm{Wm^{-2}}$



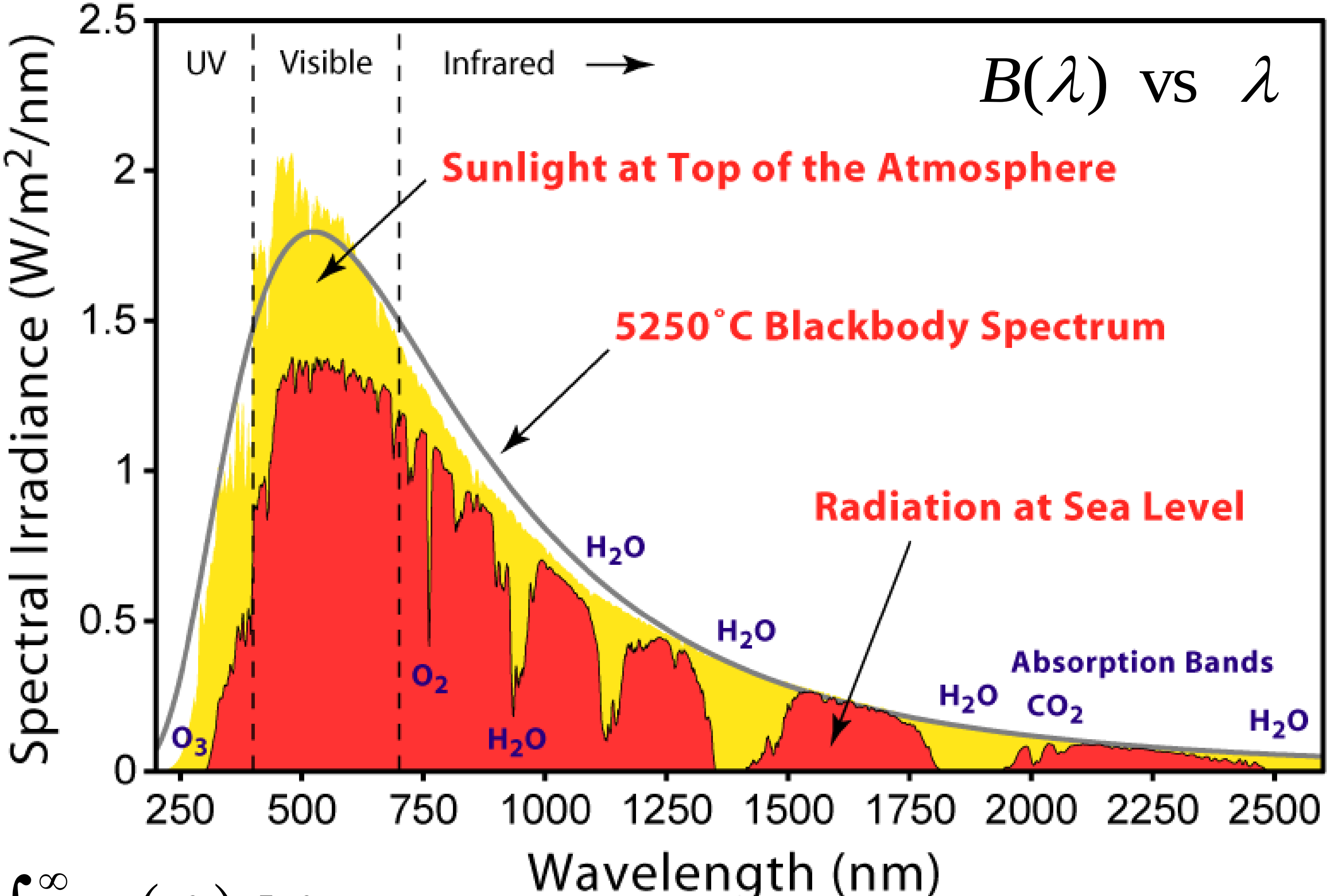
Energy Produced by 1 square meter = σT^4

Total Square Meters $A = 4\pi R^2$

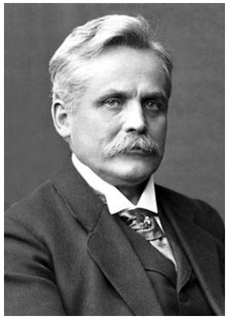
Total Energy Produced $L = (4\pi R^2)(\sigma T^4)$

The measured solar irradiance (i.e. power received on Earth per square metre within a wavelength interval i.e. $\lambda \rightarrow \lambda + d\lambda$

What is the model for $B(\lambda)$?



$$I = \int_0^\infty B(\lambda) d\lambda$$

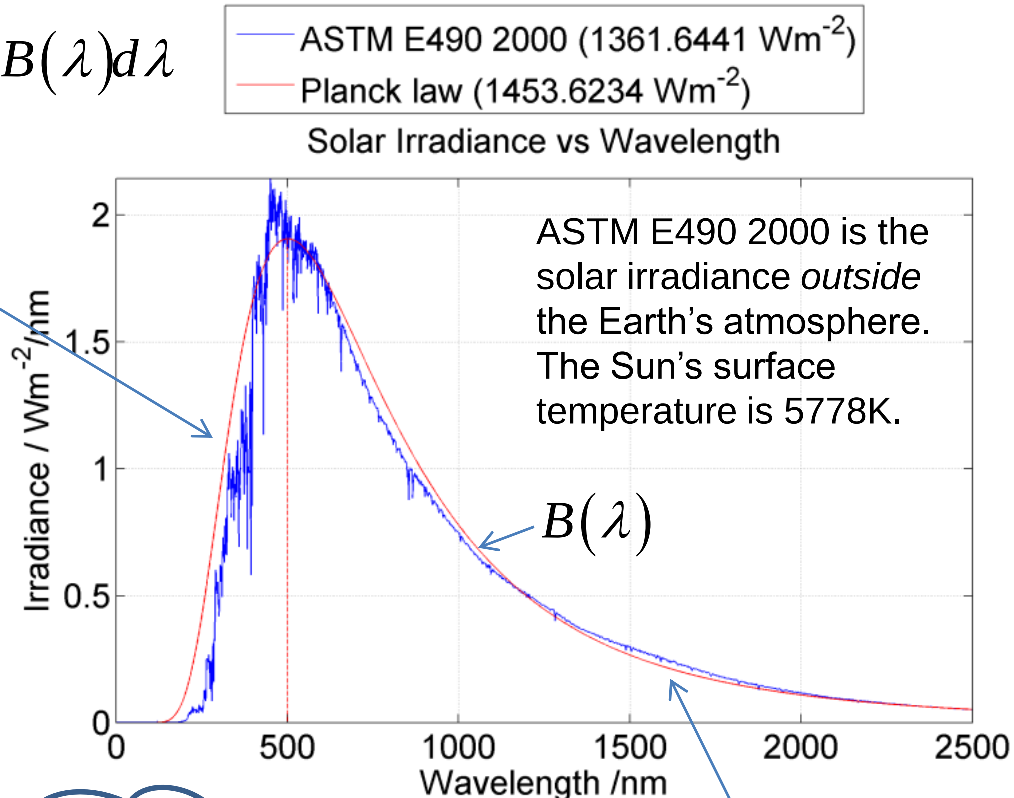


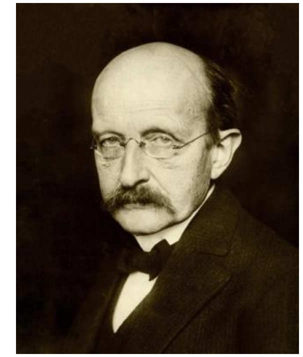
Wilhelm Wien
1864-1928

Predicted
the short wavelength
part well.....

But not the
spectrum at long
wavelengths

$$I = \int_0^\infty B(\lambda)\,d\lambda$$

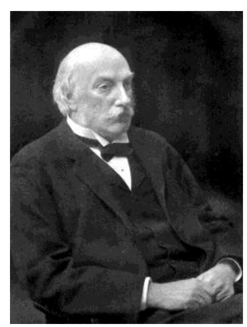




Max Planck
'guessed'
what the law
should be. But this
led to a strange
conclusion .....

$$\bar{E} = \tfrac{3}{2} k_B T$$

Max Planck
1858 – 1947



John Strutt
(Lord Rayleigh)
1842-1919

James Jeans
1877-1946

Considered
waves in a 3D box
and predicted the long
wavelength spectrum.
But an 'ultraviolet
catastrophe' at short
wavelengths!

Max Planck
1858 – 1947

Let's start from the Rayleigh-Jeans analysis

$$I = \sigma T^4 = \tfrac{1}{4} uc$$

Radiant energy flux upon the walls of a black cavity containing energy per unit volume u (from Kinetic theory).

$$u = \int_0^\infty \phi(f)\,df$$

Energy density (energy per unit volume)

$$\phi(f) = \eta \times \bar{E}$$

Energy density within frequency range

Rayleigh
Jeans

$$\eta = \frac{8\pi f^2}{c^3}$$

is the 'density of states' i,e. number of photons per unit volume that can be activated within frequency range

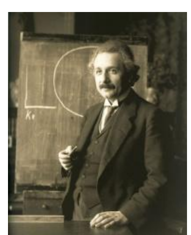
$$f \rightarrow f + df$$

But $\bar{E} = \tfrac{3}{2} k_B T$ means

$$I = \infty$$

This is the clever bit. Planck had to **quantize** radiation energy. h turned out to be very small, but *not* zero

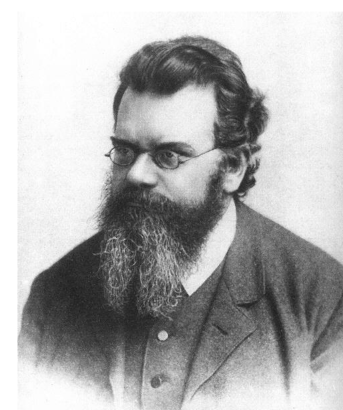
$$\bar{E} = \frac{hf}{e^{\frac{hf}{k_B T}} - 1}$$



I worked this out!

is the average energy of a *photon* of frequency f

Ludwig
Boltzmann
1844-1906

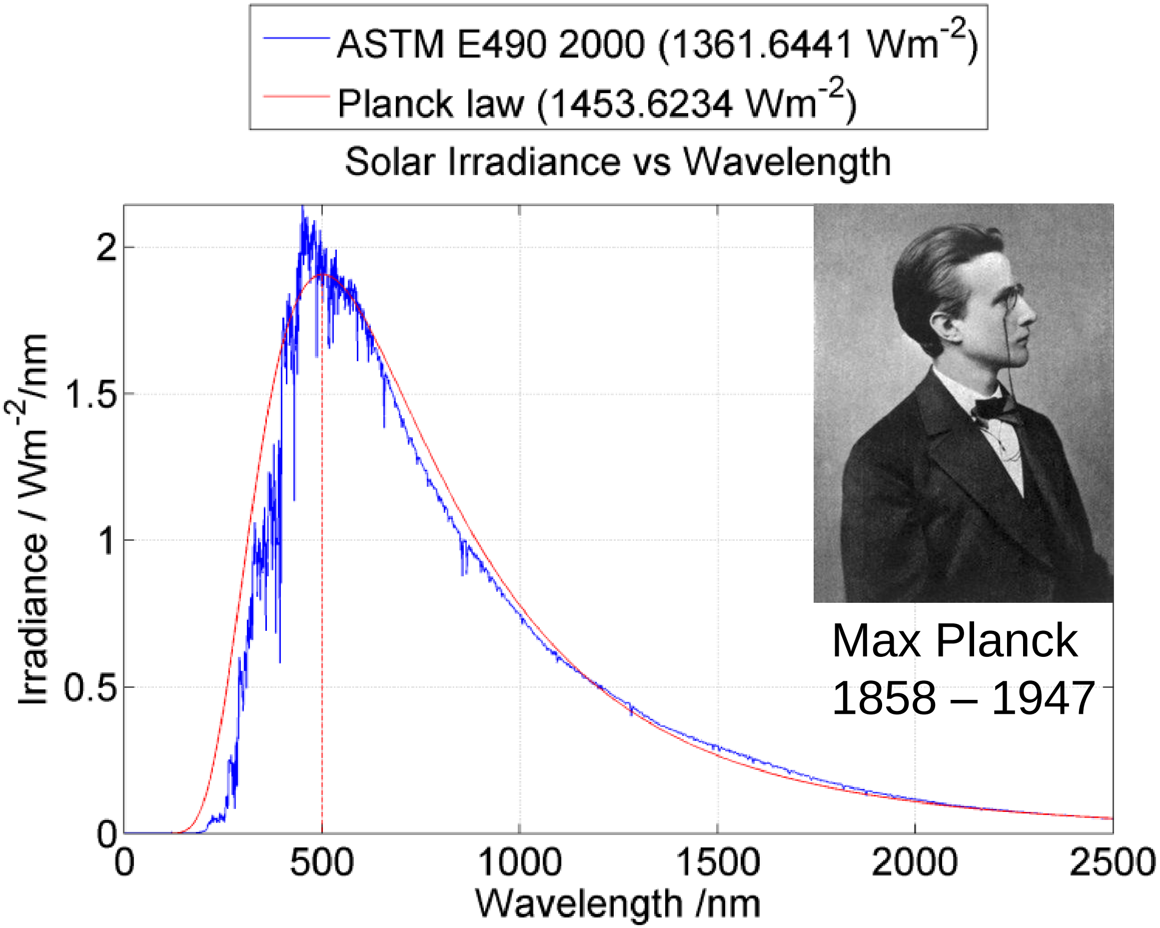


Red	620-750nm
Yellow	570-590nm
Green	495-570nm
Blue	450-495nm

Boltzmann's constant $k_B = 1.381 \times 10^{-23}\,\mathrm{m^2kgs^{-2}K^{-1}}$

Planck's constant $h = 6.626 \times 10^{-34}\,\mathrm{m^2kgs^{-1}}$

Speed of light $c = 2.998 \times 10^{8}\,\mathrm{ms^{-1}}$



Max Planck
1858 – 1947

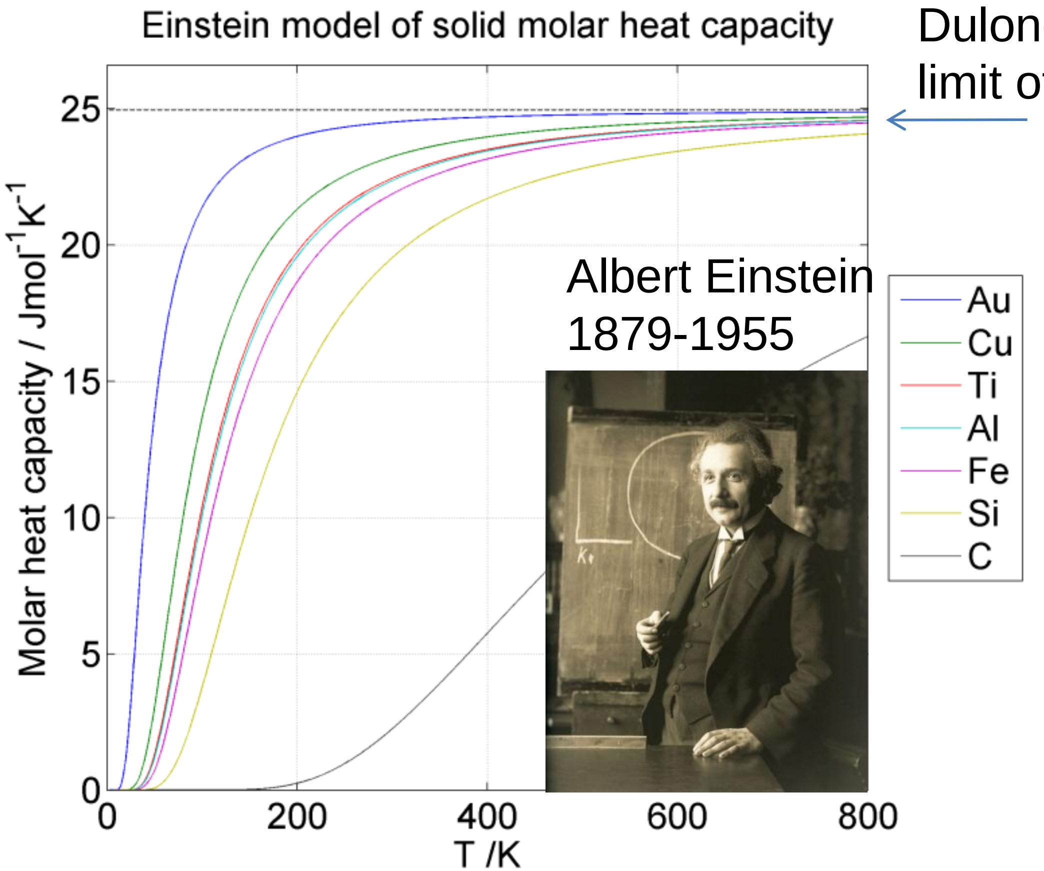
$$I = \int_0^\infty B(\lambda, T)\,d\lambda = \sigma T^4$$

$$\sigma = \frac{2\pi^5 k_B^4}{15c^2h^3}$$

$$B(\lambda, T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$$

So radiation is **quantized** into **photons** of energy

$$\boxed{E = hf}$$



Albert Einstein
1879-1955

Dulong & Petit
limit of $3R$

$$C = 3R \times \frac{x^2 e^x}{\left(e^x - 1\right)^2}$$

$$x = \frac{hf_E}{k_B T}$$

In the Einstein model, all vibrations have the same frequency.

Einstein applied the analysis of Black Body radiation to the vibrations of a solid lattice of atoms.

Although the theory is approximate,
at low temperatures, it does predict the general shape of **heat capacity** vs **temperature** for a solid

Peter Debye
1884-1966

Proposed an improved model for the heat capacity of solids

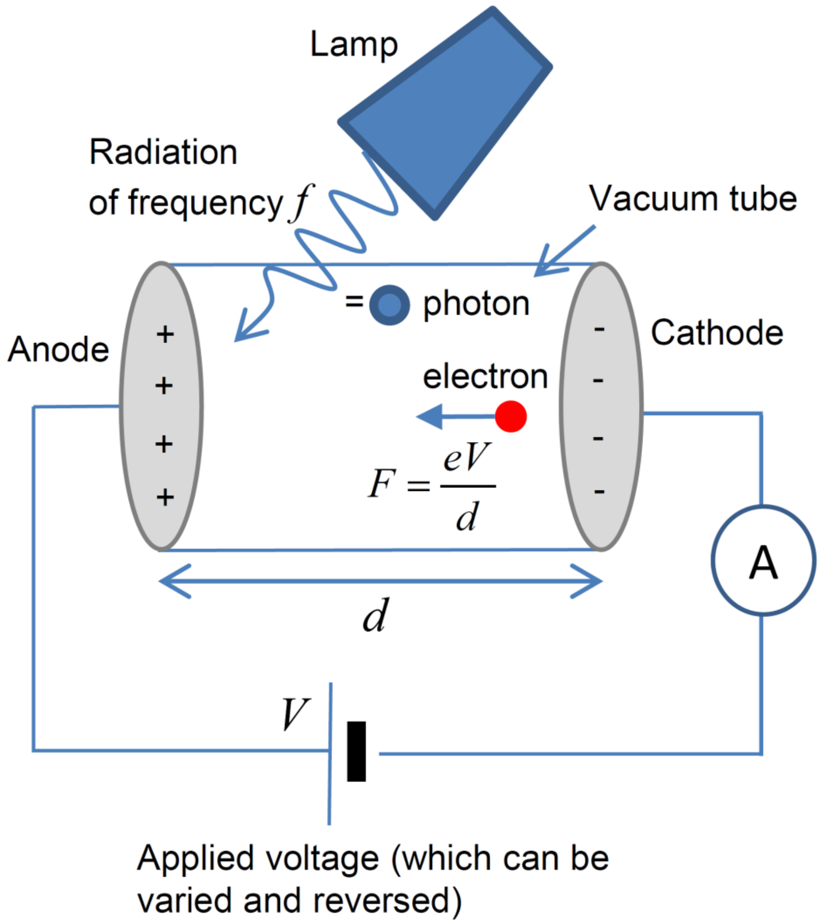
PHOTO ELECTRIC EFFECT

Kinetic energy of emitted electrons

$$\boxed{E = hf - W}$$

'Work function' or 'binding energy' of electron in the surface

Photon energy



To **stop the electrons reaching the cathode**

$$eV = E = hf - W$$

$$\therefore \boxed{V = \frac{h}{e} f - \frac{W}{e}}$$

$$f_{cutoff} = \frac{W}{h}$$

Robert Millikan 1868-1953

Light above a certain 'cuttoff' frequency causes surfaces to emit electrons.

More photons mean more electrons but the electron energy only depends of frequency

This is *not* a classical prediction!

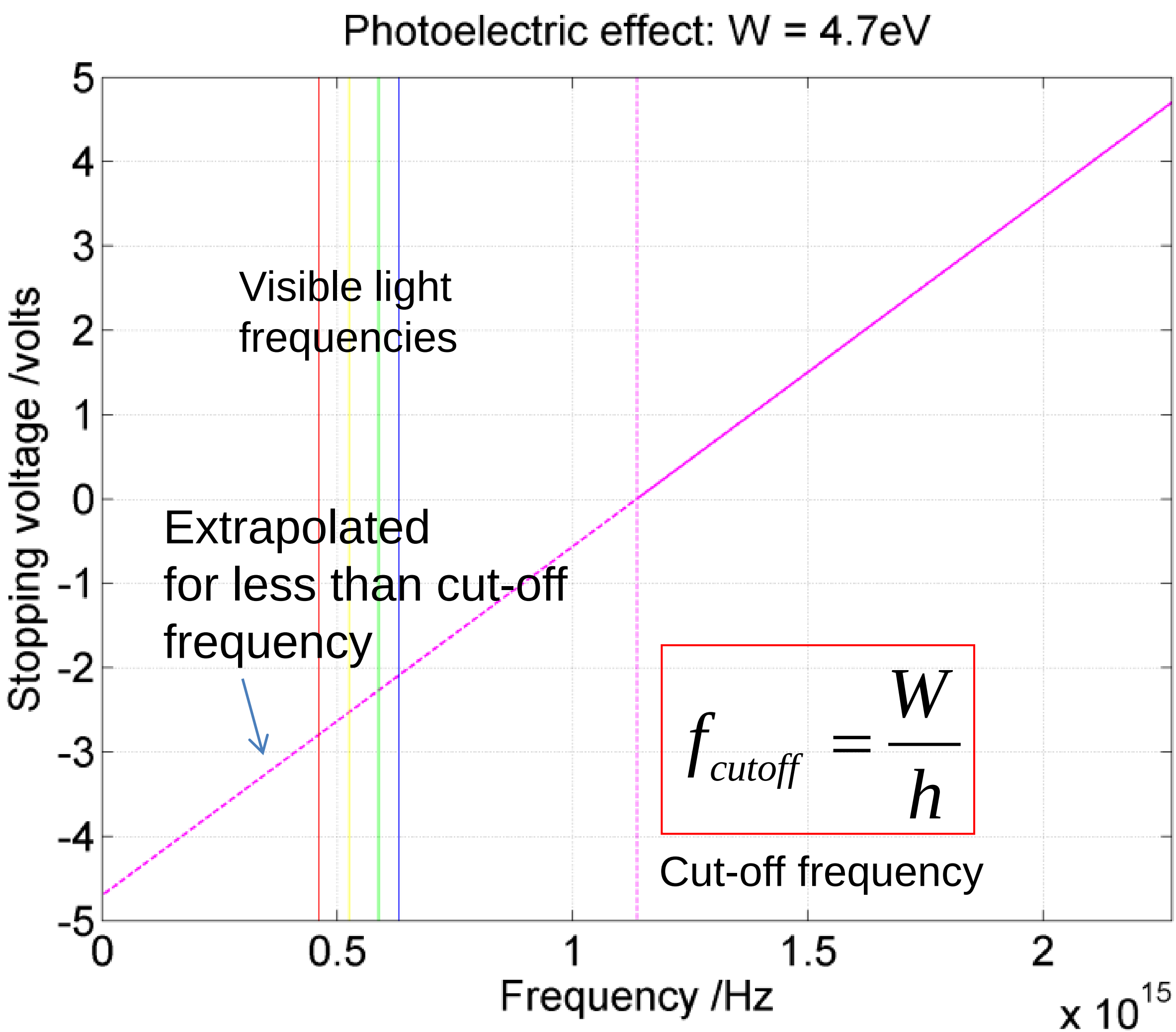
$$e = 1.6021766208(98) \times 10^{-19}\,\mathrm{C}$$ electron charge

$$eV = E = hf - W$$

$$\therefore \boxed{V = \frac{h}{e} f - \frac{W}{e}}$$

Therefore **UV light** is needed to stimulate the photoelectric effect in most metals

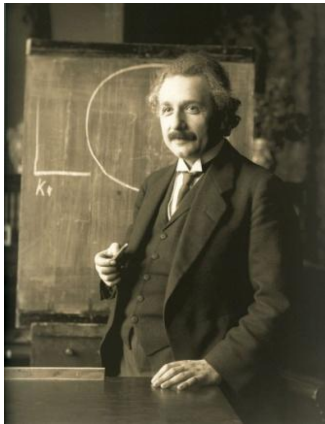
Material	Work function /eV
Silver (Ag)	4.3
Aluminium (Al)	4.3
Gold (Au)	5.1
Copper (Cu)	4.7
Tin (Sn)	4.4
Lead (Pb)	4.3
Tungsten (W)	4.5
Nickel (Ni)	4.6
Sodium (Na)	2.4



$$\boxed{f_{cutoff} = \frac{W}{h}}$$

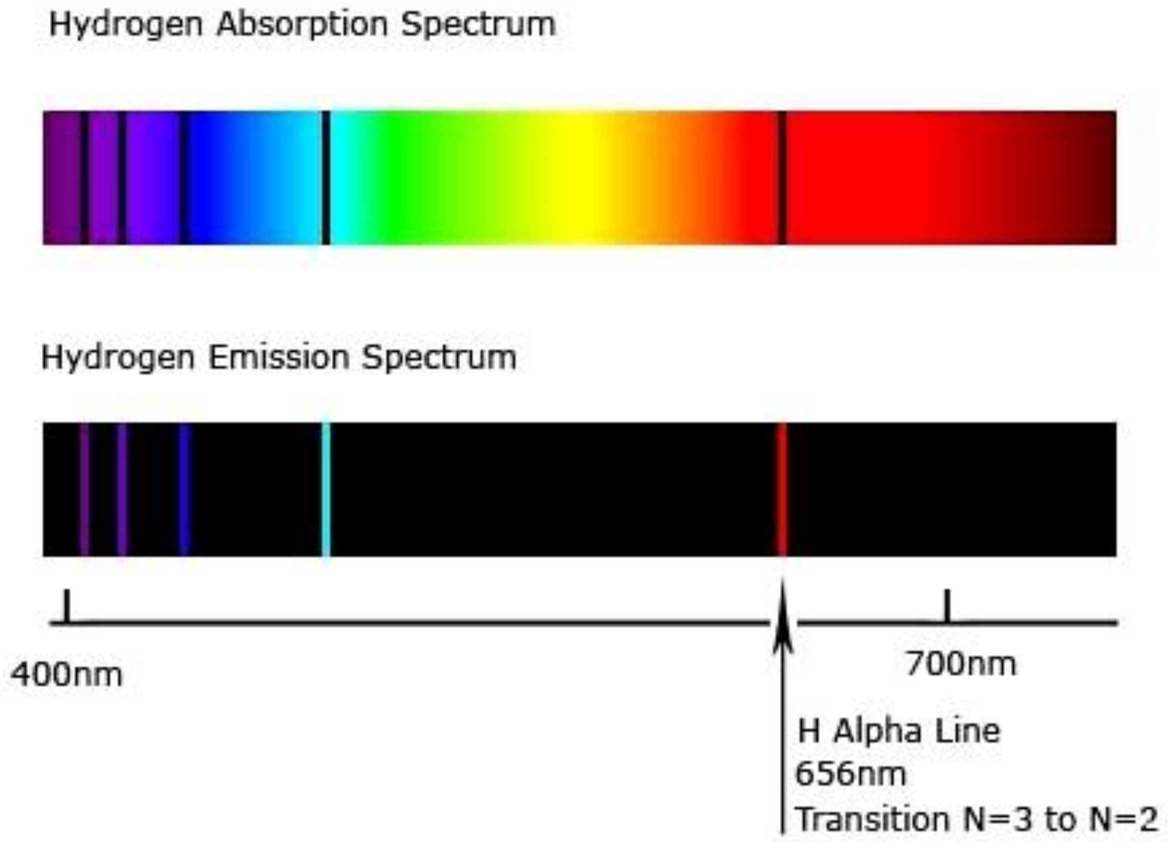
Cut-off frequency

Albert Einstein 1879-1955



Yes, me again!

HYDROGEN SPECTRA



Johann Balmer
1825-1898

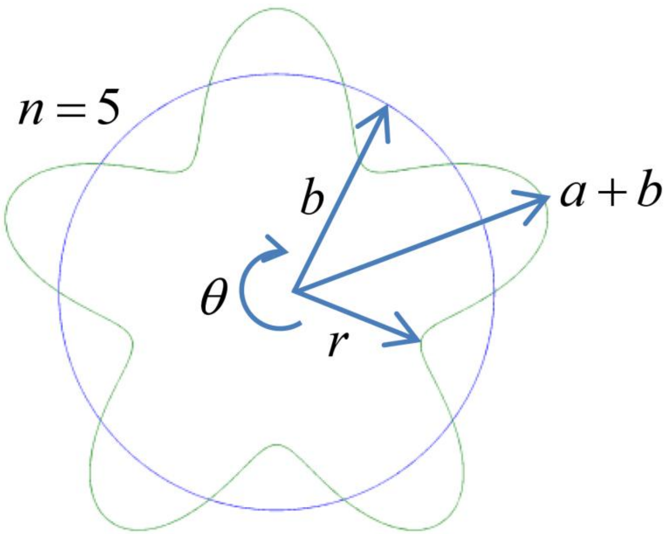
Hydrogen only re-radiates absorbed electromagnetic waves at particular frequencies. Classical Physics had no sensible explanation for this phenomenon. The Swiss Maths teacher J. Balmer proposed an empirical formula to predict the lines in the visible part of the electromagnetic spectrum

$$\boxed{\lambda_n = 91.13\,\mathrm{nm}\left(\frac{1}{m^2} - \frac{1}{n^2}\right)^{-1}} \qquad n \geq 3, m = 2$$

The strange formula can be explained by combining quantum ideas from de Broglie and Bohr, and a bit of classical physics

Louis de Broglie
1892 –1987

Niels Bohr
1885-1962



Electrons are 'standing waves' around the nucleus

$$2\pi r = n\lambda$$

n is an **integer**

de Broglie relationship

$$\boxed{m_e v = \frac{h}{\lambda}}$$

momentum

'Circular sine waves' of the form

$$r = a\sin n\theta + b$$

$$n\lambda = 2\pi b \quad \text{for waves to 'fit'}$$

$$\therefore r = a\sin\left(2\pi \times \frac{b\theta}{\lambda}\right) + b$$

$$\therefore m_e v = \frac{nh}{2\pi r}$$

Angular momentum is *quantized*!

$$\therefore \boxed{m_e r v = n\hbar}$$

$$\boxed{m_e r_n v_n = n\hbar}$$

From Classical Physics

Total energy of electron in orbit about a nucleus of charge Ze

$$E_n = -\frac{Ze^2}{8\pi\varepsilon_0 r_n}$$

Circular orbits, Coulomb force ...

$$\therefore E_n = -\frac{Ze^2}{8\pi\varepsilon_0} \times \frac{m_e Ze^2}{4\pi\varepsilon_0 n^2 \hbar^2}$$

for Hydrogen
Z = 1

$$E_n = -\frac{m_e Z^2 e^4}{8\varepsilon_0^2 h^2}\frac{1}{n^2} \approx \boxed{\frac{-13.6\mathrm{eV}}{n^2}}$$

$$\therefore hf_{nm} = E_n - E_m$$ Photon energy

$$hf_{nm} = \frac{m_e Z^2 e^4}{8\varepsilon_0^2 h^2}\left(\frac{1}{m^2} - \frac{1}{n^2}\right)$$

$$f_{nm} = \frac{m_e Z^2 e^4}{8\varepsilon_0^2 h^3}\left(\frac{1}{m^2} - \frac{1}{n^2}\right)$$

$$c = f_{nm}\lambda_{nm}$$

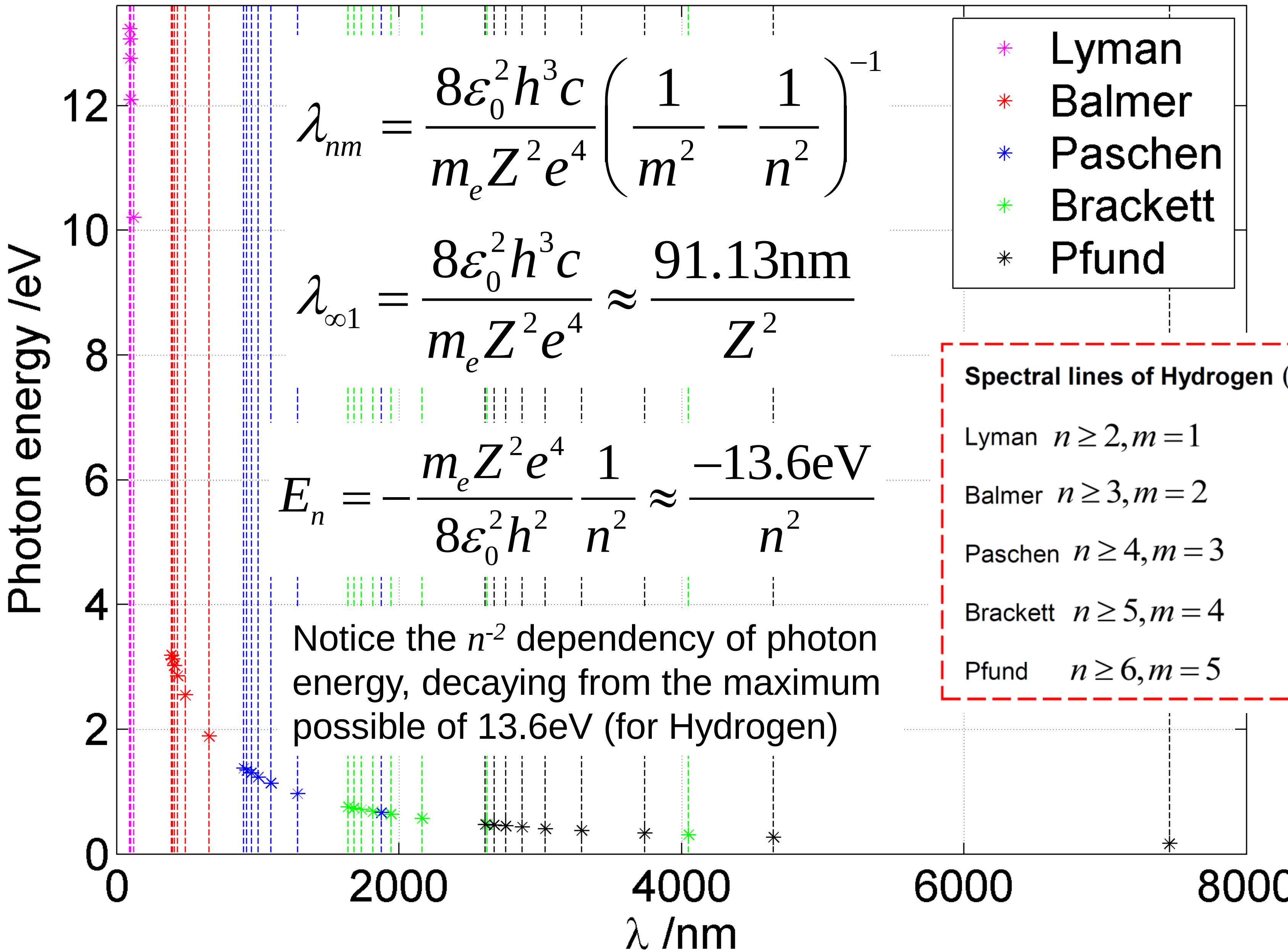
$$\lambda_{nm} = \frac{c}{f_{nm}}$$

$$\boxed{\lambda_{nm} = \frac{8\varepsilon_0^2 h^3 c}{m_e Z^2 e^4}\left(\frac{1}{m^2} - \frac{1}{n^2}\right)^{-1}}$$

$$\lambda_{\infty 1} = \frac{8\varepsilon_0^2 h^3 c}{m_e Z^2 e^4} \approx \frac{91.13\mathrm{nm}}{Z^2}$$

i.e. photons are emitted when electron energies change from one quantum state to another

Bohr model of Hydrogenic atom photon emissions: Z = 1



$$\lambda_{nm} = \frac{8\varepsilon_0^2 h^3 c}{m_e Z^2 e^4}\left(\frac{1}{m^2} - \frac{1}{n^2}\right)^{-1}$$

$$\lambda_{\infty 1} = \frac{8\varepsilon_0^2 h^3 c}{m_e Z^2 e^4} \approx \frac{91.13\text{nm}}{Z^2}$$

$$E_n = -\frac{m_e Z^2 e^4}{8\varepsilon_0^2 h^2}\frac{1}{n^2} \approx \frac{-13.6\text{eV}}{n^2}$$

Notice the n^{-2} dependency of photon energy, decaying from the maximum possible of 13.6eV (for Hydrogen)

Spectral lines of Hydrogen $(Z=1)$

Lyman $n \geq 2, m = 1$

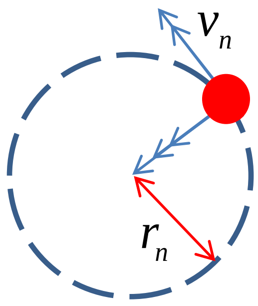
Balmer $n \geq 3, m = 2$

Paschen $n \geq 4, m = 3$

Brackett $n \geq 5, m = 4$

Pfund $n \geq 6, m = 5$

Orbital velocity



$$v_n = \frac{n\hbar}{m_e r_n}$$

$$v_n = \frac{1}{n}\frac{\hbar m_e Z e^2}{m_e 4\pi\varepsilon_0 \hbar^2} = \frac{Ze^2}{4\pi\varepsilon_0 \hbar}\frac{1}{n}$$

$$v_n = \frac{\alpha Z}{n} c$$

This is called the **Fine Structure Constant**
Note it is dimensionless!

$$\alpha = \frac{e^2}{4\pi\varepsilon_0 \hbar c} \approx \frac{1}{137}$$

So electrons can ‘orbit’ about 1% of the speed of light. This is large enough for **relativistic effects** to be apparent.

Careful inspection of the Hydrogen emission spectrum shows indeed a small deviation from the Balmer formula

ELECTRON DIFFRACTION

$$eV = \tfrac{1}{2} m_e v^2$$

$$p = m_e v$$

$$\therefore eV = \tfrac{1}{2} m_e \left(\frac{p}{m_e} \right)^2 = \frac{p^2}{2m_e}$$

$$p = \sqrt{2m_e eV}$$

$$\boxed{\lambda = \frac{h}{\sqrt{2m_e eV}}}$$

Apply **relativity** and you get a small correction to this formula

Louis de Broglie
1892 –1987

All particles have an associated wave

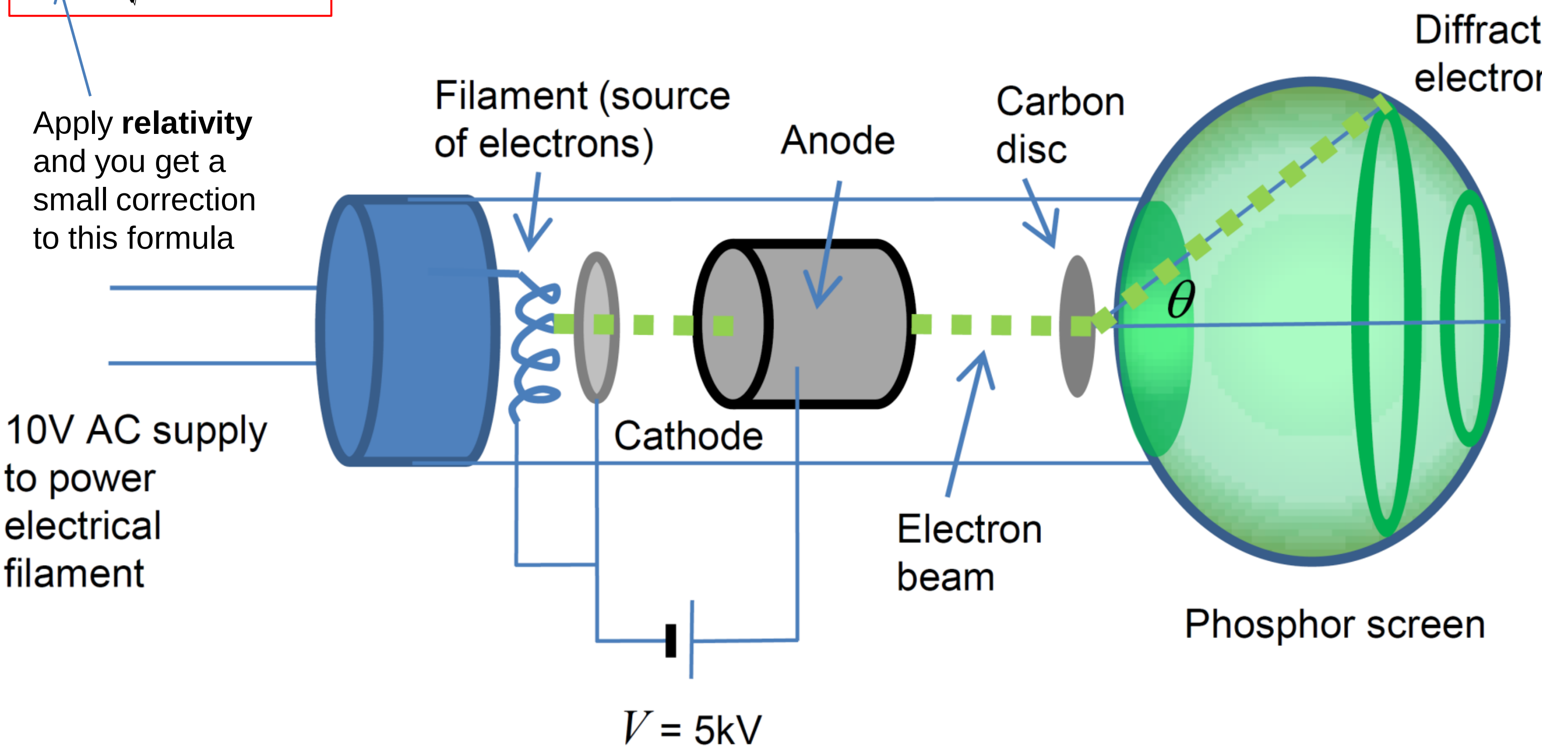
wavelength

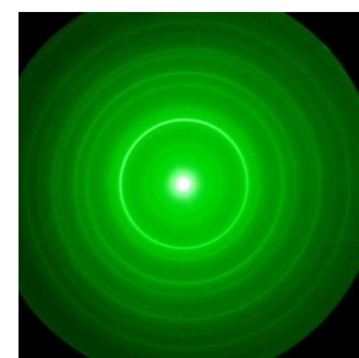
$$\lambda = \frac{h}{p}$$

Planck's constant

momentum

Lester Germer (right) with Clinton Davisson in 1927

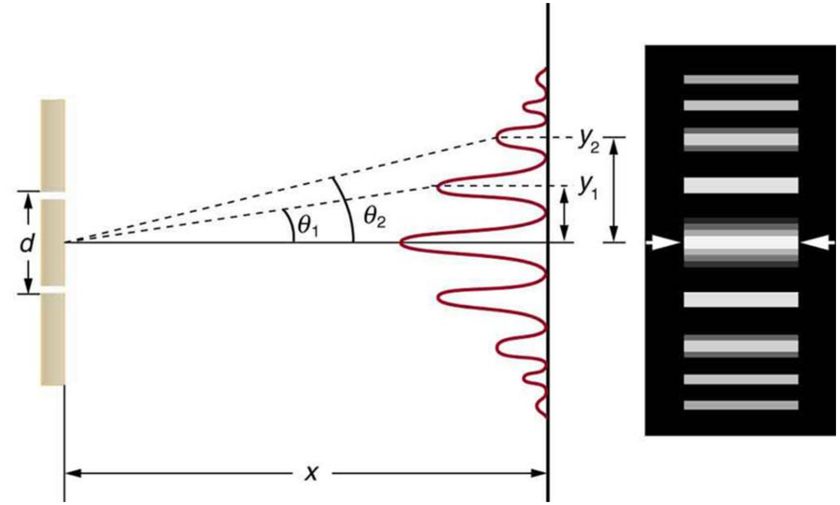




Young's slits and photons

Thomas Young
1773-1829

Young's double slits cause incident waves to diffract, resulting in an **interference pattern**



$$\psi(r,t) \approx \frac{Ae^{i(kr-\omega t)}}{r}\left(e^{-i\frac{1}{2}kd\sin\theta} + e^{i\frac{1}{2}kd\sin\theta}\right)$$

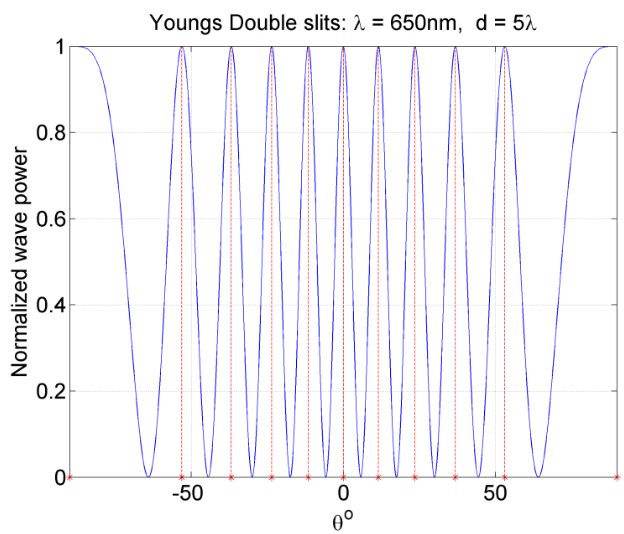
$$\psi(r,t) \approx \frac{2Ae^{i(kr-\omega t)}}{r}\cos\left(\tfrac{1}{2}kd\sin\theta\right)$$

$$\boxed{|\psi|^2 \approx \frac{A^2}{r^2}\cos^2\left(\tfrac{1}{2}kd\sin\theta\right)}$$

Hence *maxima* when

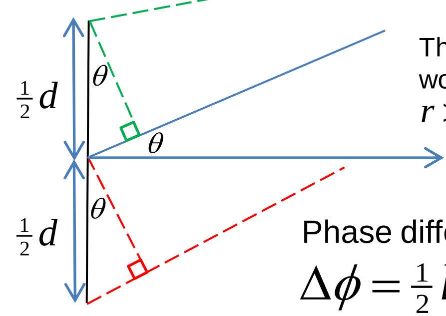
$$\tfrac{1}{2}kd\sin\theta = n\pi$$

$$\theta = \sin^{-1}\left(\frac{2n\pi}{kd}\right) = \boxed{\sin^{-1}\left(\frac{n\lambda}{d}\right)}$$



Equivalent geometry is wavelet sources are at the same angle (i.e. *plane waves*) but separated by $d\sin\theta$

Phase difference
$\Delta\phi = -\tfrac{1}{2}kd\sin\theta$

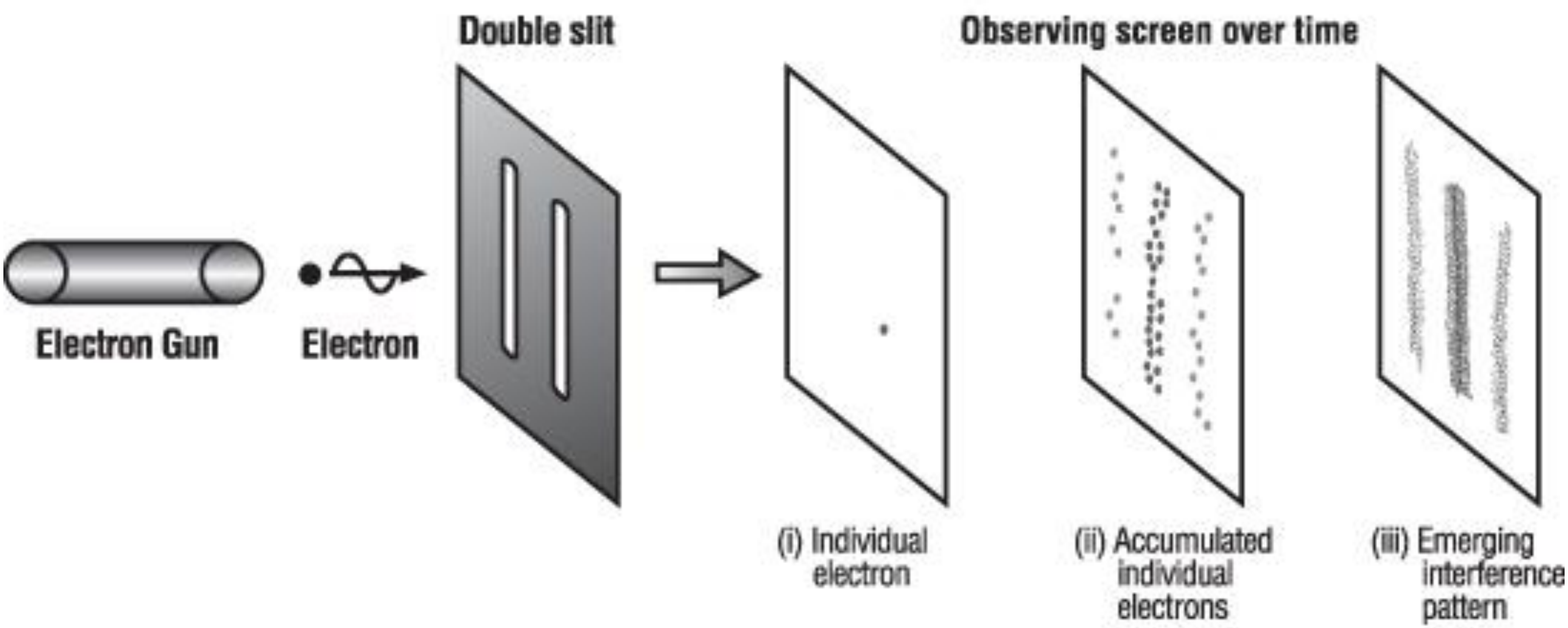


This only works because $r \gg d$

Phase difference
$\Delta\phi = \tfrac{1}{2}kd\sin\theta$

Amazingly, the same interference pattern is seen if single electrons are fired through a double slit arrangement. The wavefunction appears to interfere in exactly the same way as if the electron were an electromagnetic wave.

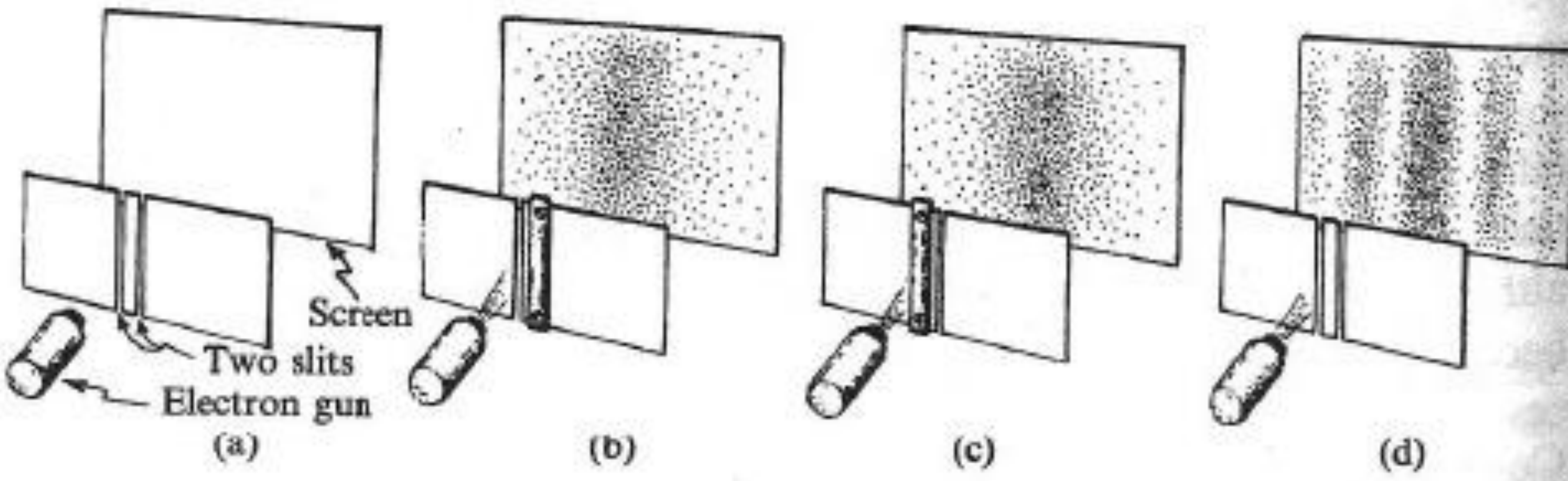
Electron wavelength from de-Broglie relation $\lambda = \dfrac{h}{p}$



Double-slit apparatus showing the pattern of electron hits on the observing screen building up over time.

If one of the slits is blocked off, the *interference pattern is broken*.

Does the electron go through 'both slits at the same time' ?



(a) Arrangement for the two-slit experiment. One electron is emitted at a time, aimed at the screen through the pair of slits. (b) Pattern on the screen when the right-hand slit is covered. (c) The same, when the left-hand slit is covered. (d) Interference occurs when both slits are open. Some regions on the screen cannot now be reached despite the fact that they can be with just one or the other slit open.

THE WAVE EQUATION & UNCERTAINTY PRINCIPLE

Combine:

Wave amplitude

The wave equation

$$\boxed{\frac{\partial^2 \psi}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 \psi}{\partial t^2}}$$

Conservation of energy

$$\boxed{E = \frac{p^2}{2m} + V}$$

de-Broglie relation

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

Erwin Schrödinger
1887 – 1961

$$-\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2}+V\psi=E\psi$$

Erwin Schrödinger
1887 – 1961

$$-\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2}+V\psi=i\hbar\frac{\partial\psi}{\partial t}$$

Schrödinger Equation

Max Born
1882 – 1970

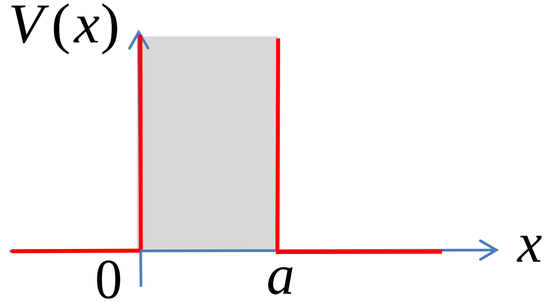
Born interpretation

$$\left|\psi(x,t)\right|^2 dx$$

is the *probability* of
a particle being at location
between x and $x + dx$

Particle in a box

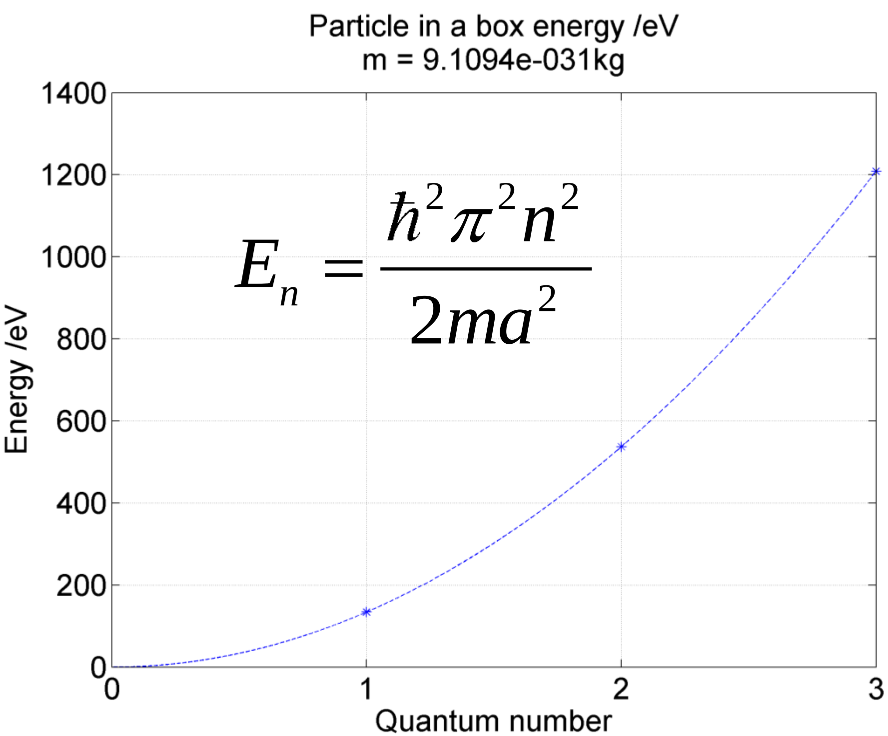
$$V(x)=\begin{cases}\infty & x\le 0,\ x\ge a\\ 0 & 0<x<a\end{cases}$$



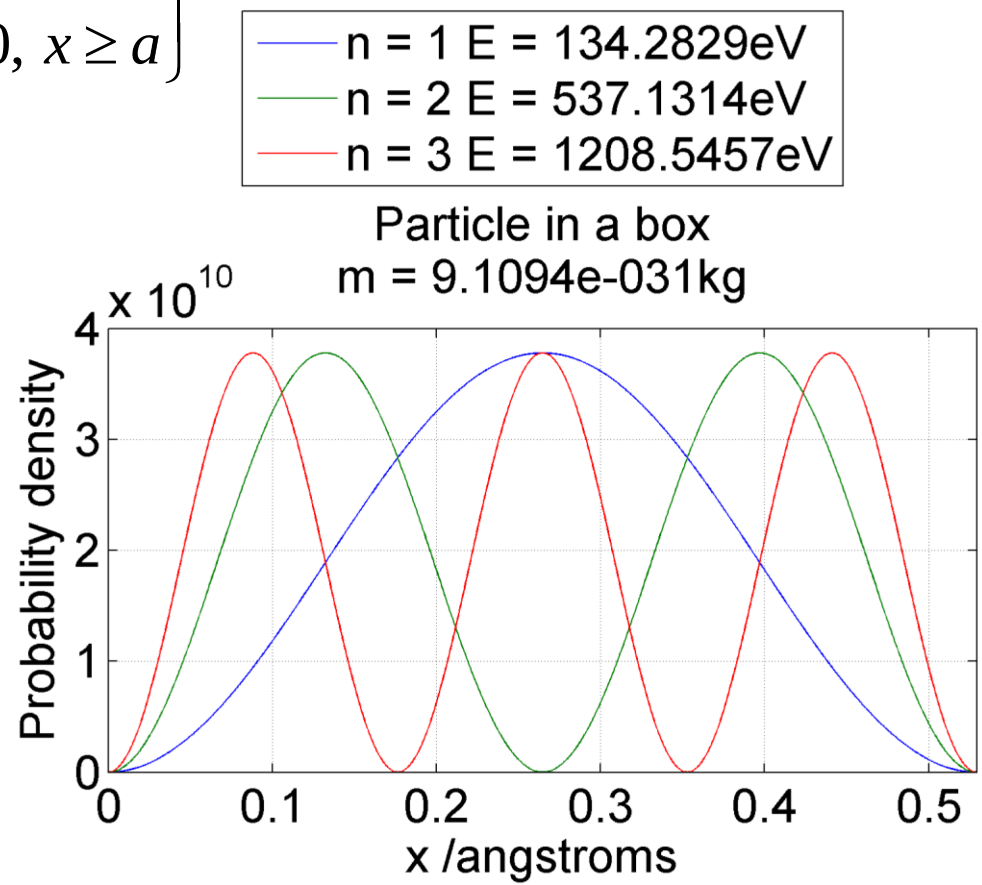
$$-\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2}+V\psi=i\hbar\frac{\partial\psi}{\partial t}$$

Schrödinger Equation

$$\psi_n(x,t)=\begin{cases}\sqrt{\frac{2}{a}}e^{-\frac{iEt}{\hbar}}\sin\left(\frac{n\pi x}{a}\right) & 0<x<a\\ 0 & x\le 0,\ x\ge a\end{cases}$$

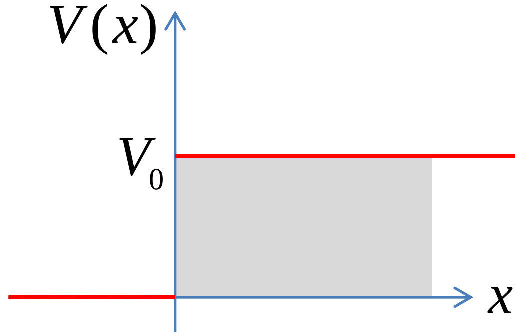


$$E_n=\frac{\hbar^2\pi^2n^2}{2ma^2}$$



Potential step

$$V(x) = \begin{cases} V_0 & x \geq 0 \\ 0 & x < 0 \end{cases}$$



$$-\frac{\hbar^2}{2m}\frac{\partial^2 \psi}{\partial x^2} + V\psi = i\hbar \frac{\partial \psi}{\partial t}$$

$$k = \frac{\sqrt{2mE}}{\hbar}$$

$$q = \frac{\sqrt{2m\left(E - V_0\right)}}{\hbar}$$

$$r = \frac{k-q}{k+q}$$

$$t = \frac{2k}{k+q}$$

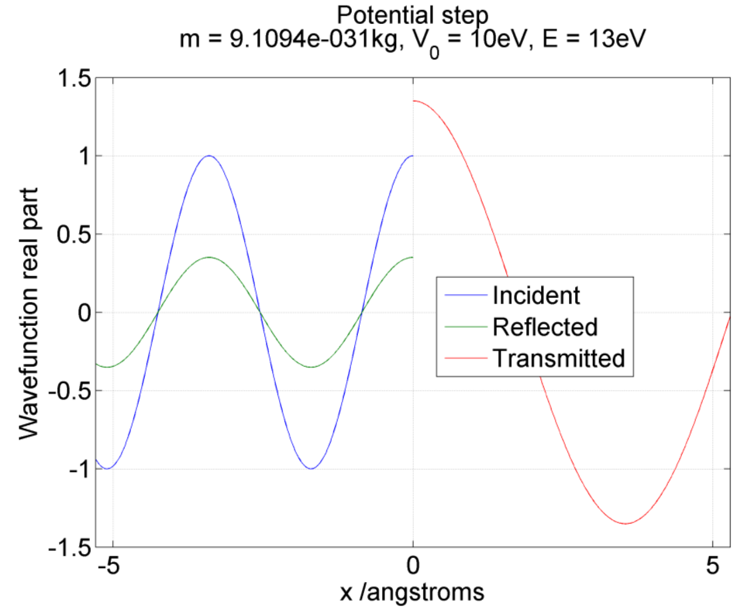
$$\psi = \psi_0 e^{ikx} e^{-\frac{iEt}{\hbar}}$$

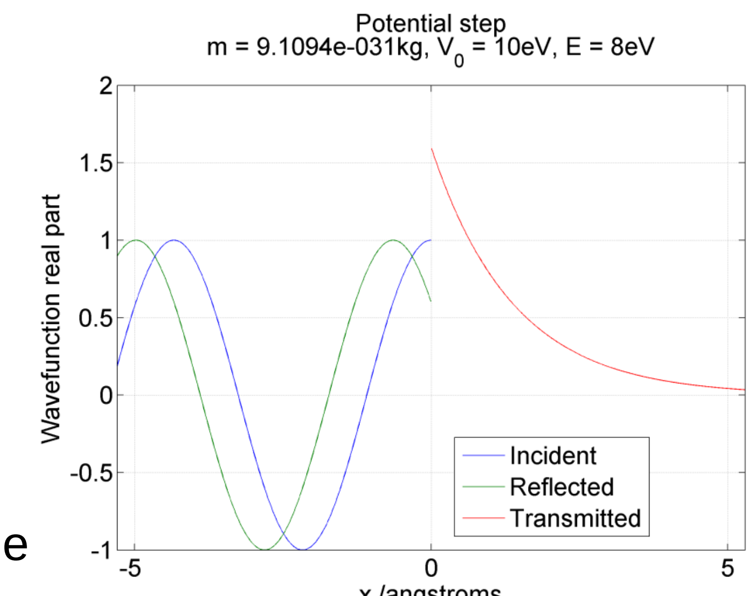
Wavefunction of incident particle

$$\psi = \begin{cases} r\psi_0 e^{-ikx} e^{-\frac{iEt}{\hbar}} & x < 0 \\ t\psi_0 e^{iqx} e^{-\frac{iEt}{\hbar}} & x \geq 0 \end{cases}$$

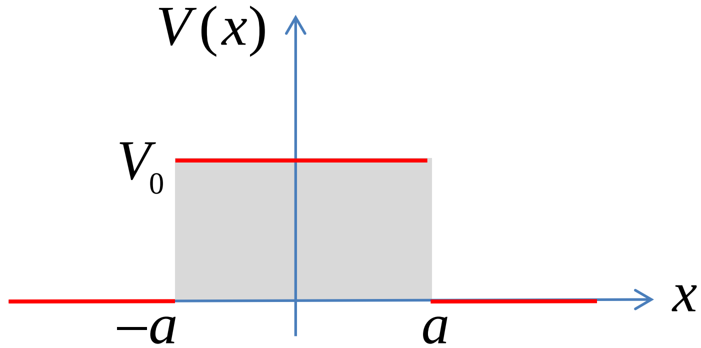
Wavefunction of reflected particle ($x < 0$)

Wavefunction of transmitted particle ($x \geq 0$)





Potential barrier "Tunnelling"



$$-\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2}+V\psi=i\hbar\frac{\partial\psi}{\partial t}$$

Schrödinger Equation

$$V(x)=\begin{cases}V_0 & |x|\le a\\ 0 & |x|>a\end{cases}$$

$$k=\frac{\sqrt{2mE}}{\hbar}$$

$$q=\frac{\sqrt{2m(V_0-E)}}{\hbar}$$

$$r=\frac{-ie^{-2ika}(k^2+q^2)\sinh 2qa}{2kq\cosh 2qa-i\left(k^2-q^2\right)\sinh 2qa}$$

$$t=\frac{2kqe^{-2ika}}{2kq\cosh 2qa-i\left(k^2-q^2\right)\sinh 2qa}$$

This assumes $E<V_0$

$qa \ll 1$

$|t|^2 \approx e^{-2qa}$

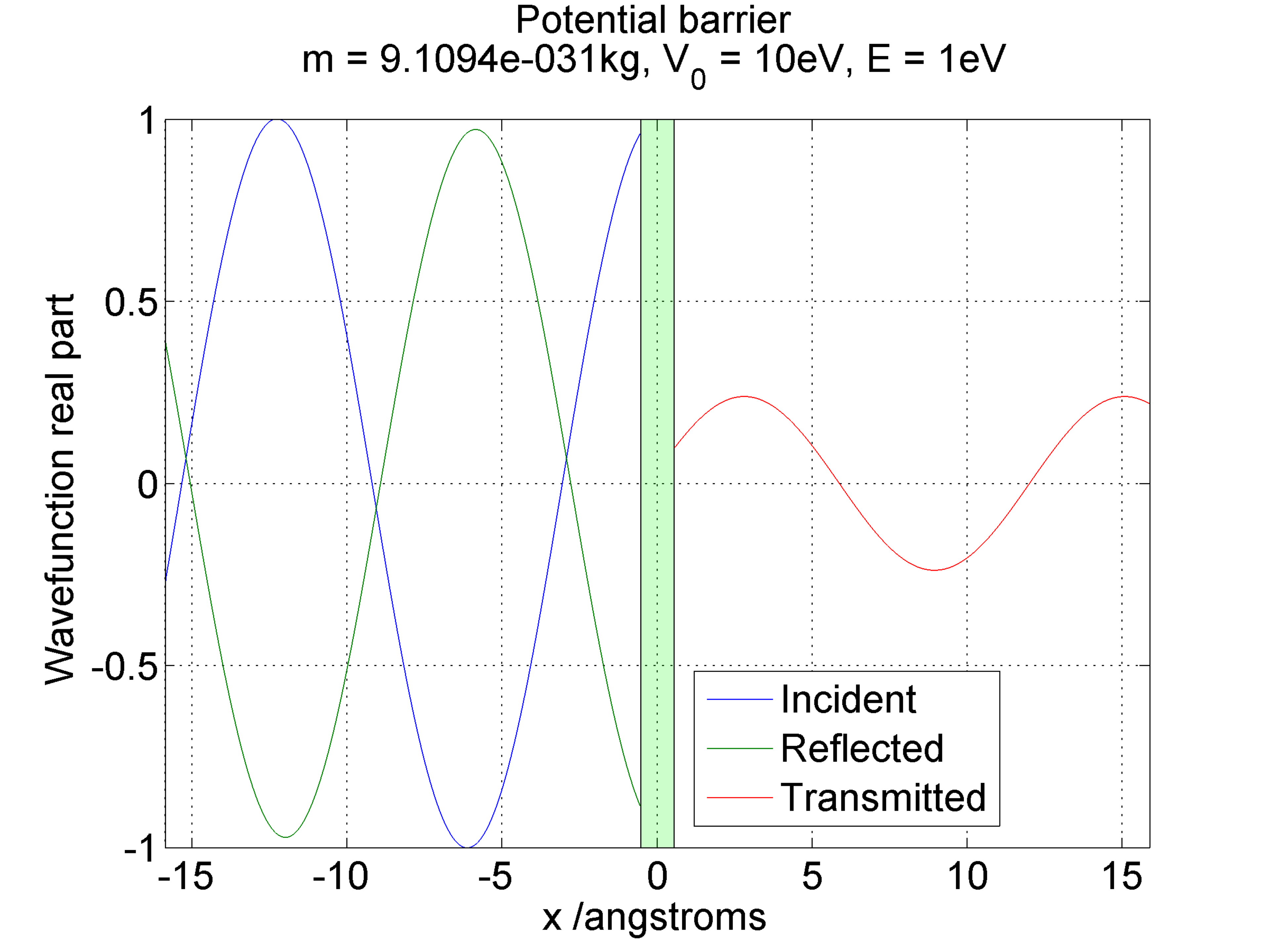
$$\psi=\psi_0 e^{ikx}e^{-\frac{iEt}{\hbar}}$$

Wavefunction of incident particle

$$\psi=\begin{cases} r\psi_0 e^{-ikx}e^{-\frac{iEt}{\hbar}} & x<-a \\ t\psi_0 e^{ikx}e^{-\frac{iEt}{\hbar}} & x\ge a\end{cases}$$

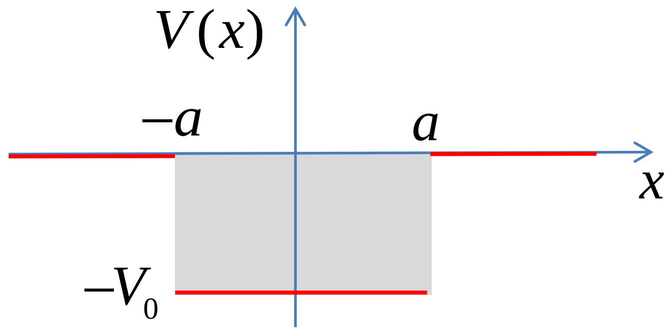
Wavefunction of reflected particle ($x<-a$)

Wavefunction of transmitted particle ($x\ge a$)


Potential barrier
m = 9.1094e-031kg, V0 = 10eV, E = 1eV
Wavefunction real part
x /angstroms
Incident
Reflected
Transmitted
1
0.5
0
-0.5
-1
-15
-10
-5
0
5
10
15

Potential well

$$V(x)=\begin{cases}-V_0 & |x|\le a\\ 0 & |x|>a\end{cases}$$



$$-\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2}+V\psi=i\hbar\frac{\partial\psi}{\partial t}$$

Schrödinger Equation

$$k=\frac{\sqrt{2mE}}{\hbar}$$

$$q=\frac{\sqrt{2m\left(E+V_0\right)}}{\hbar}$$

$$r=\frac{ie^{-2ika}(q^2-k^2)\sin 2qa}{2kq\cos 2qa-i\left(k^2+q^2\right)\sin 2qa}$$

$$t=\frac{2kqe^{-2ika}}{2kq\cos 2qa-i\left(k^2+q^2\right)\sin 2qa}$$

This assumes $E>0$

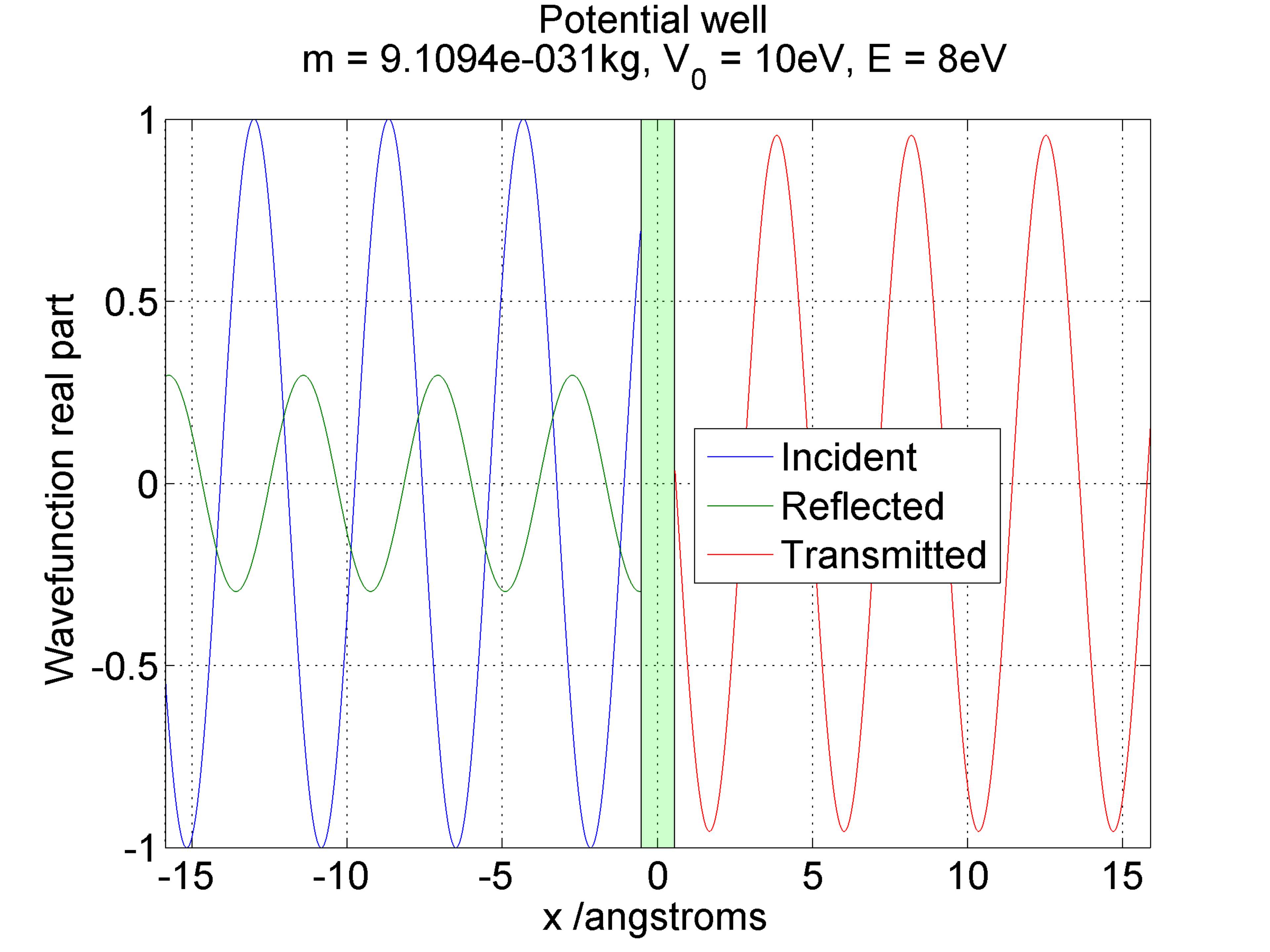
$$\psi=\psi_0 e^{ikx}e^{-\frac{iEt}{\hbar}}$$

Wavefunction of incident particle

$$\psi=\begin{cases}r\psi_0 e^{-ikx}e^{-\frac{iEt}{\hbar}} & x<-a\\ t\psi_0 e^{ikx}e^{-\frac{iEt}{\hbar}} & x\ge a\end{cases}$$

Wavefunction of reflected particle ($x<-a$)

Wavefunction of transmitted particle ($x\ge a$)



Potential well
m = 9.1094e-031kg, V0 = 10eV, E = 8eV
Wavefunction real part
x /angstroms
Incident
Reflected
Transmitted
1
0.5
0
-0.5
-1
-15
-10
-5
0
5
10
15

Harmonic oscillator

$$V(x) = \tfrac{1}{2} m\omega^2 x^2$$

$$\psi_n(x,t) = \frac{e^{-\frac{x^2}{2a^2}}}{\sqrt{2^n a\sqrt{\pi} n!}} H_n\left(\frac{x}{a}\right) e^{-\frac{iEt}{\hbar}}$$

$$a = \sqrt{\frac{\hbar}{m\omega}}$$

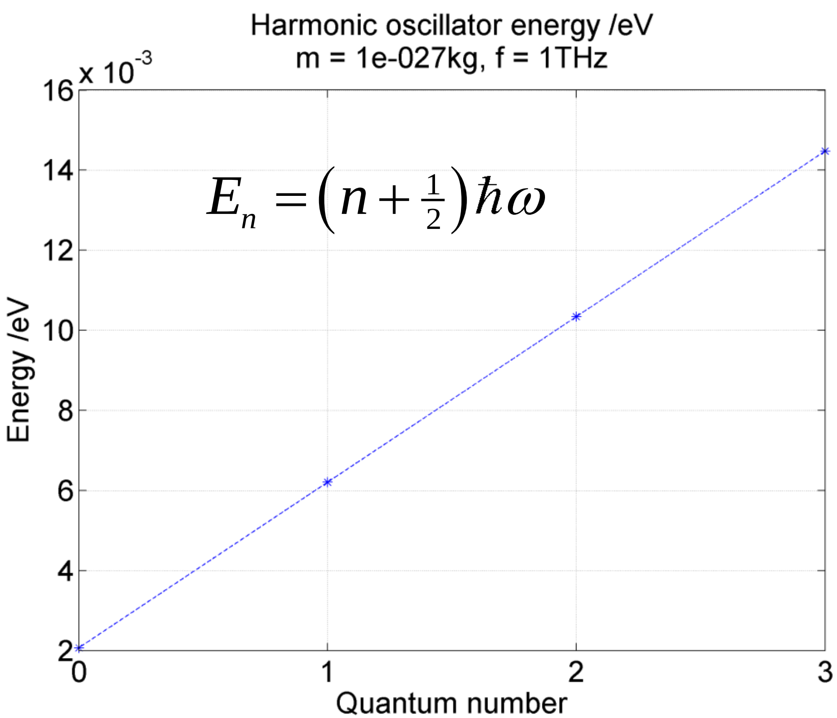
Angular frequency of oscillator $\omega = 2\pi f$

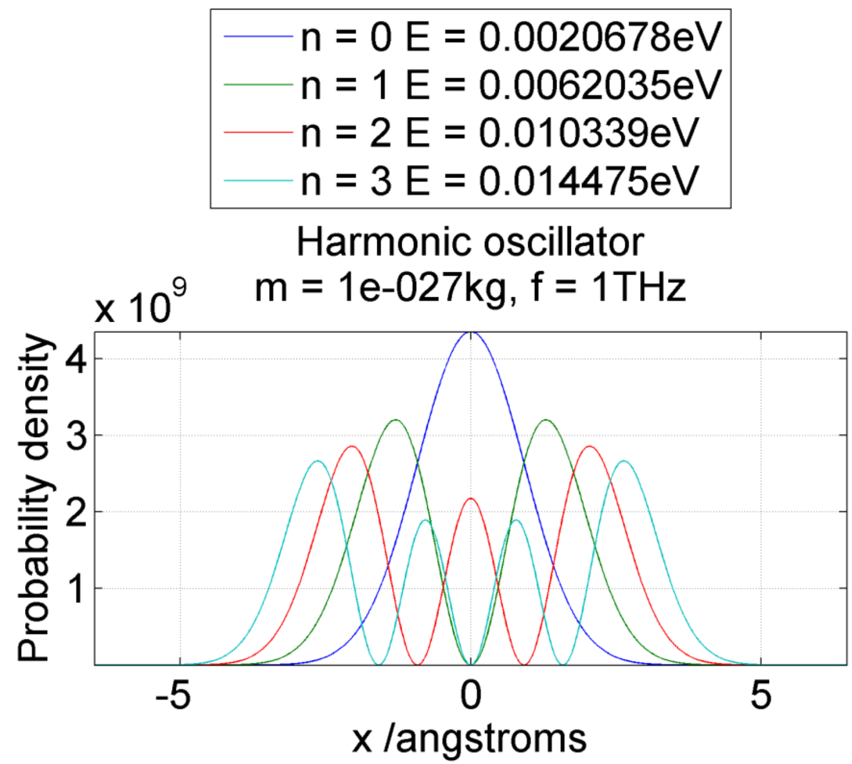
$$-\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2} + V\psi = i\hbar\frac{\partial \psi}{\partial t}$$

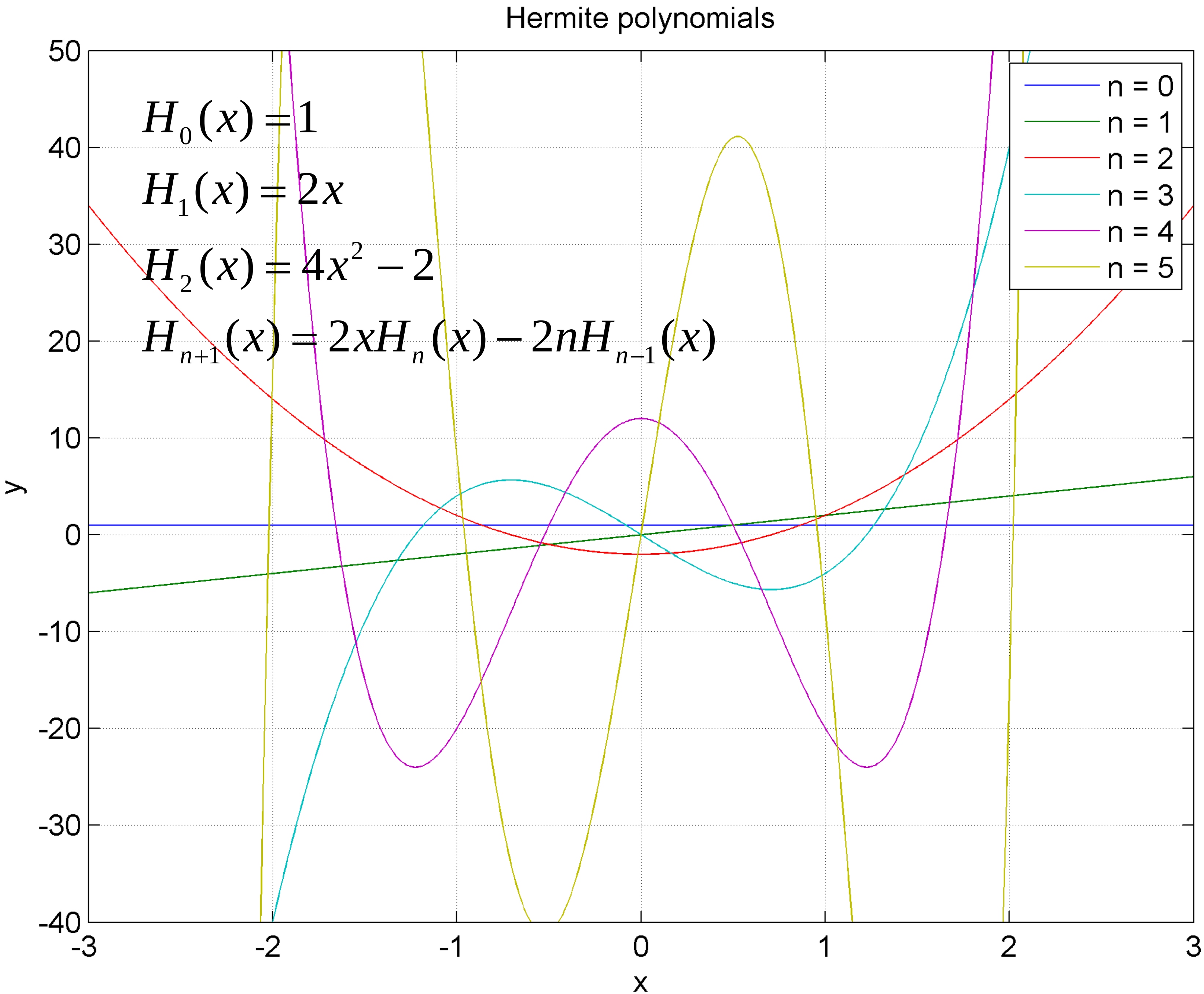
Schrödinger Equation

$$H_0(z) = 1$$
$$H_1(z) = 2z$$
$$H_2(z) = 4z^2 - 2$$
$$H_{n+1}(z) = 2zH_n(z) - 2nH_{n-1}(z)$$

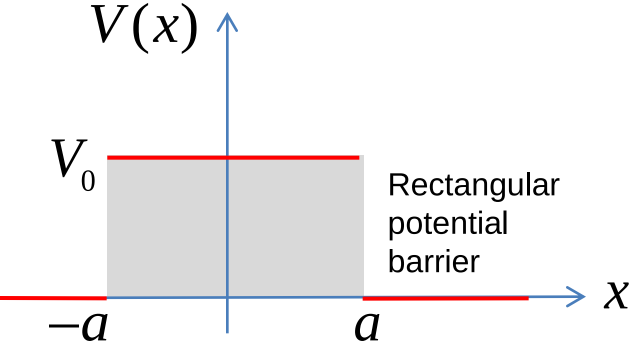
Hermite polynomials







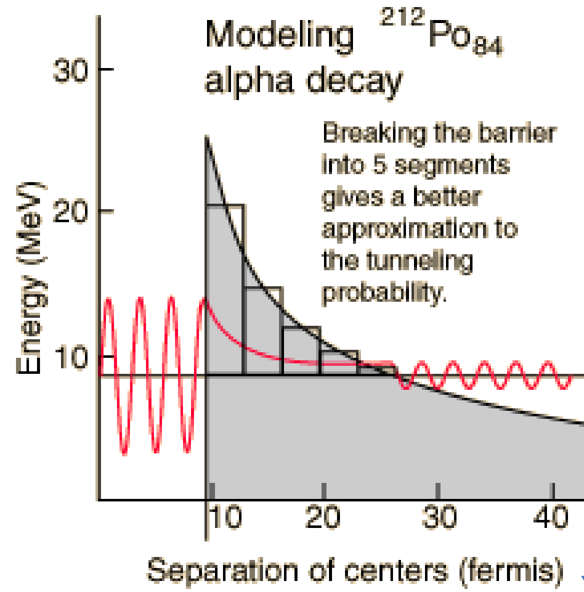
Hermite polynomials
$H_0(x) = 1$
$H_1(x) = 2x$
$H_2(x) = 4x^2 - 2$
$H_{n+1}(x) = 2xH_n(x) - 2nH_{n-1}(x)$
n = 0
n = 1
n = 2
n = 3
n = 4
n = 5
y
x
50
40
30
20
10
0
-10
-20
-30
-40
-3
-2
-1
0
1
2
3



Gamow model of alpha decay

Gasiorowicz, *Quantum Physics*

George Gamow 1904-1968



$10^{-15}\,\mathrm{m}$

$$q = \frac{\sqrt{2m\left(V_0 - E\right)}}{\hbar}$$

$$qa \ll 1$$

$$|t|^2 \approx e^{-2qa}$$ Tunnelling probability

"Lifetime of alpha particle = time to traverse nucleus / probability of alpha escaping"

$$P = \prod_n e^{-2q_n \delta r}$$ let coulomb barrier be lots of thin rectangles

$$q_n = \frac{\sqrt{2m}}{\hbar}\sqrt{\frac{2(Z-2)e^2}{r_n} - E}$$

$$E = \tfrac{1}{2}mv^2$$

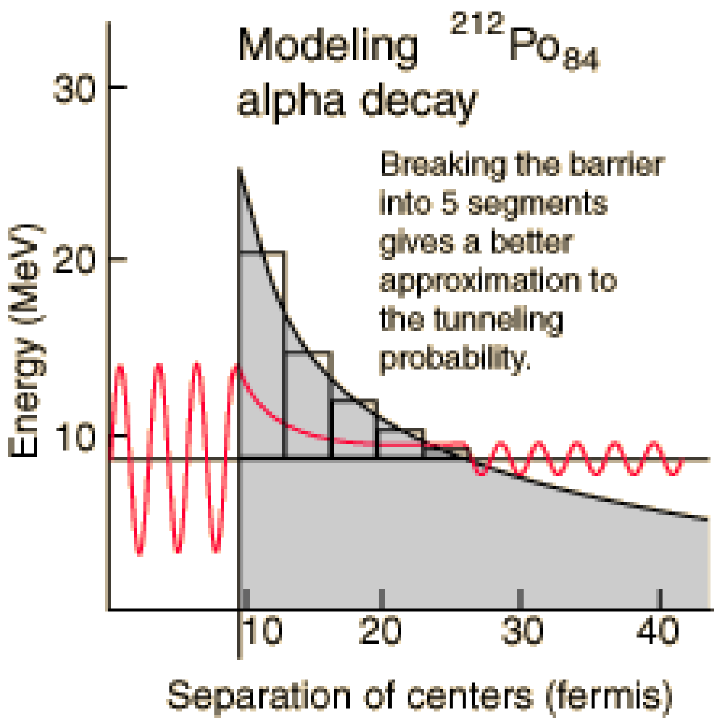
$$\tau \approx \frac{2R}{v} \div e^{-G} = 2R\sqrt{\frac{m}{2E}}e^{G}$$

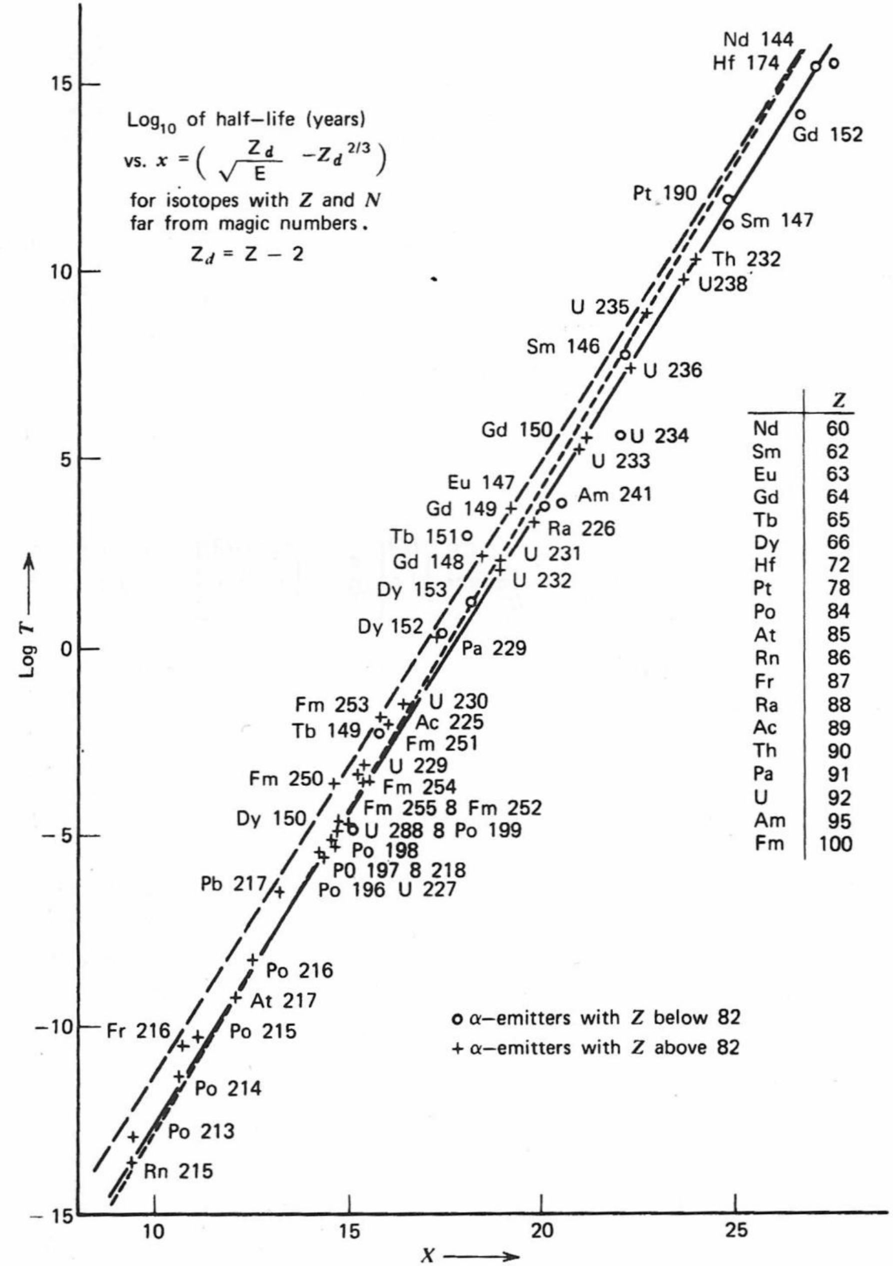
$$G = 2\left(\frac{2m}{\hbar^2}\right)^{1/2}\int_R^b\left(\frac{2(Z-2)e^2}{r} - E\right)^{1/2} dr$$

Half life of alpha-emmitter

$$\log_{10} T_{\frac{1}{2}} \approx 1.61 \times \frac{Z-2}{\sqrt{E_\alpha}} - 28.9 - 1.6\left(Z-2\right)^{\frac{2}{3}}$$

$$E_\alpha \approx 1\mathrm{MeV}$$





Plot of $\log_{10} 1/\tau$ versus $C_2 - C_1 Z_1/\sqrt{E}$ with $C_1 = 1.61$ and a slowly varying $C_2 = 28.9 + 1.6Z_1^{2/3}$. From E. K. Hyde, I. Perlman, and G. T. Seaborg, *The Nuclear Properties of the Heavy Elements*, Vol. 1, Prentice-Hall, Englewood Cliffs, N.J. (1964)

Gasiorowicz, *Quantum Physics* pp87

Hydrogenic atom

Reduced mass $\mu = \frac{m_e M}{m_e + M} = \frac{m_e}{\frac{m_e}{M}+1} \approx m_e$

Nucleus mass M

Electron mass m_e

$$-\frac{\hbar^2}{2\mu}\frac{\partial^2 \psi}{\partial x^2} + V\psi = i\hbar\frac{\partial \psi}{\partial t}$$

Schrödinger Equation

$$V(r) = -\frac{Ze^2}{4\pi\varepsilon_0 r}$$

$$\psi_{nlm}\left(r,\theta,\phi\right) = R(r,n,l)\times\Omega\left(\theta,\phi,l,m\right)$$

Angular wavefunction

$$R(r,n,l) = \sqrt{\frac{(n-l-1)!}{2n(n+l)!}\left(\frac{2}{an}\right)^{3/2}}\; x^l e^{-x/2}\zeta(x,l,n)$$

Radial wavefunction

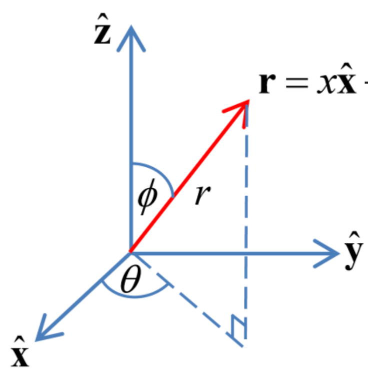
$$\zeta(x,l,n) = \sum_{k=0}^{n-l-1}\frac{(l+n)!(-x)^k}{(2l+1+k)!(n-l-1-k)!k!}$$

Lageurre polynomial

$$x = \frac{2r}{an}$$

$$E_n = -\frac{\mu e^4 Z^2}{8\varepsilon_0^2 h^2 n^2}$$

Orbital energy



$$\boxed{\begin{aligned} x &= r\sin\phi\cos\theta \\ y &= r\sin\phi\sin\theta \\ z &= r\cos\phi \end{aligned}}$$

Conversion between Cartesian and polar coordinates

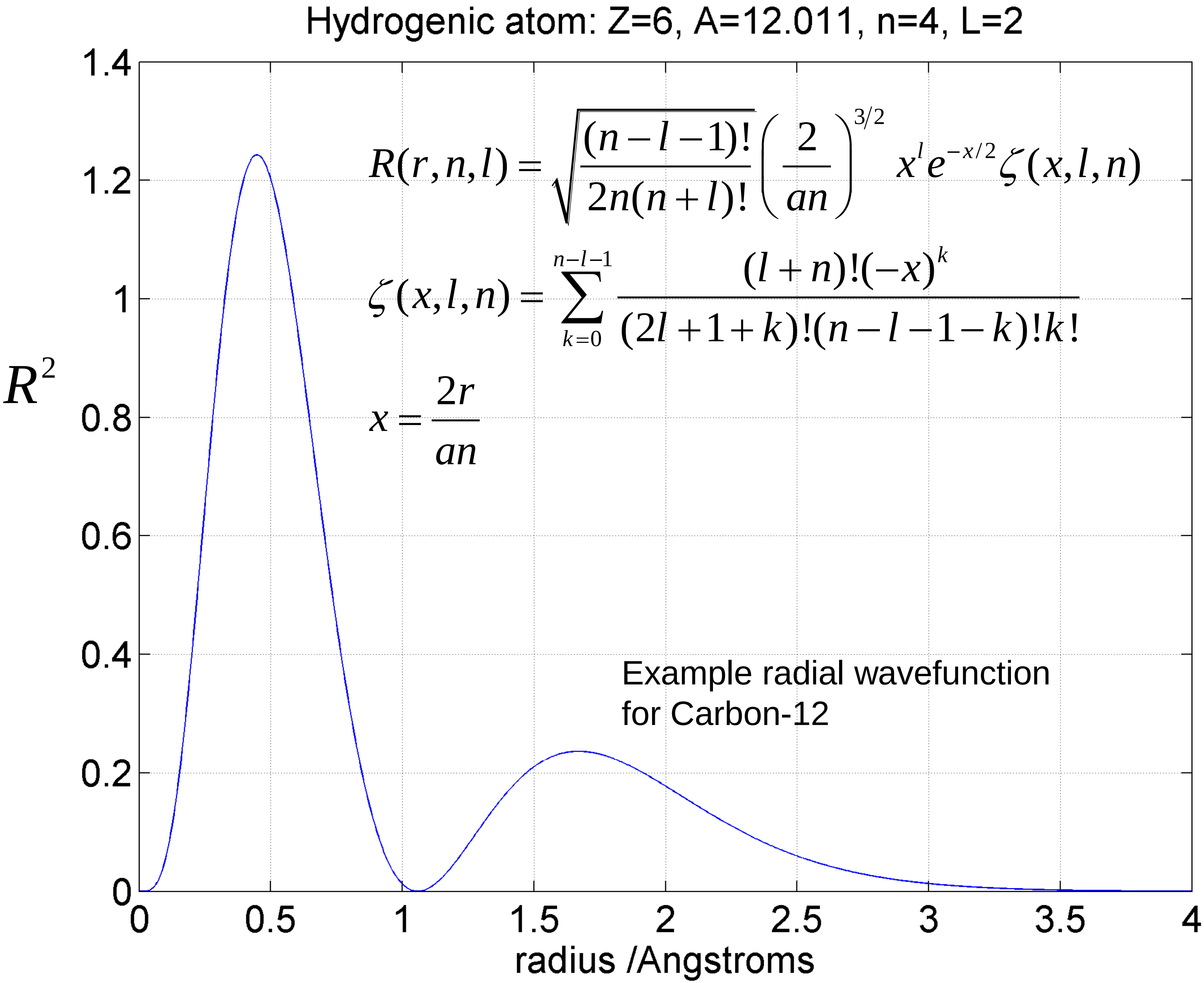
Polar coordinate unit vectors as Cartesian coordinates

$$\hat{\mathbf{r}} = \sin\phi\cos\theta\hat{\mathbf{x}} + \sin\phi\sin\theta\hat{\mathbf{y}} + \cos\phi\hat{\mathbf{z}}$$

$$\hat{\boldsymbol{\theta}} = -\sin\theta\hat{\mathbf{x}} + \cos\theta\hat{\mathbf{y}}$$

$$\hat{\boldsymbol{\phi}} = \cos\phi\cos\theta\hat{\mathbf{x}} + \cos\phi\sin\theta\hat{\mathbf{y}} - \sin\phi\hat{\mathbf{z}}$$

Woan, *The Cambridge Handbook of Physics Formulas*


Hydrogenic atom: Z=6, A=12.011, n=4, L=2
$R(r,n,l) = \sqrt{\frac{(n-l-1)!}{2n(n+l)!}} \left(\frac{2}{an}\right)^{3/2} x^l e^{-x/2} \zeta(x,l,n)$
$\zeta(x,l,n) = \sum_{k=0}^{n-l-1} \frac{(l+n)!(-x)^k}{(2l+1+k)!(n-l-1-k)!k!}$
$x = \frac{2r}{an}$
Example radial wavefunction
for Carbon-12
R^2
radius /Angstroms
0
0.2
0.4
0.6
0.8
1
1.2
1.4
0
0.5
1
1.5
2
2.5
3
3.5
4

Angular wavefunction

Assume quantum numbers n,l,m are integers!

$$\Omega(\theta,\phi,l,m) = \begin{cases} Y_l^{-m}(\theta,\phi) - Y_l^{-m}(\theta,\phi) & m<0 \\ Y_l^{0}(\theta,\phi) & m=0 \\ Y_l^{m}(\theta,\phi) + Y_l^{-m}(\theta,\phi) & m\geq 0 \end{cases}$$

Spherical harmonics

$$Y_l^m(\theta,\phi) = (-1)^m \left[\frac{2l+1}{4\pi} \frac{(l-m)!}{(l+m)!} \right]^{1/2} P_l^m(\cos\theta) e^{im\phi} \qquad m = -l,\ldots 0 \ldots l$$

$$\frac{d}{dx}\left[\left(1-x^2\right) \frac{dy}{dx} \right] + \left[l(l+1) - \frac{m^2}{1-x^2} \right] y = 0$$

$$y = P_l^m(x)$$

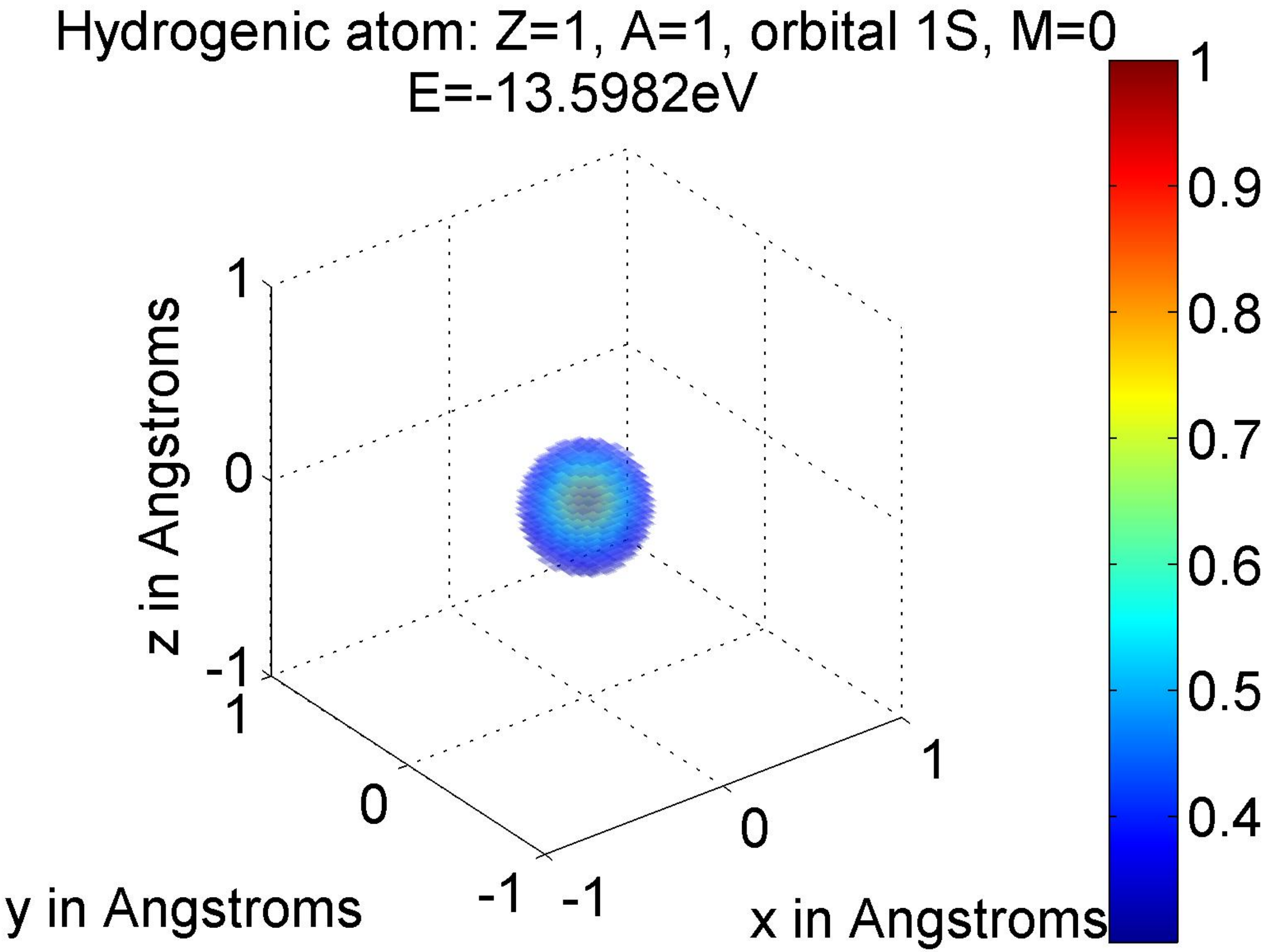
Legendre Polynomials can be evaluated using the MATLAB `legendre(`l,x`)` function (which gives a vector of outputs for all possible m values).

S

$n = 1, 2, 3, \ldots$

$l = 0$

$m = 0$



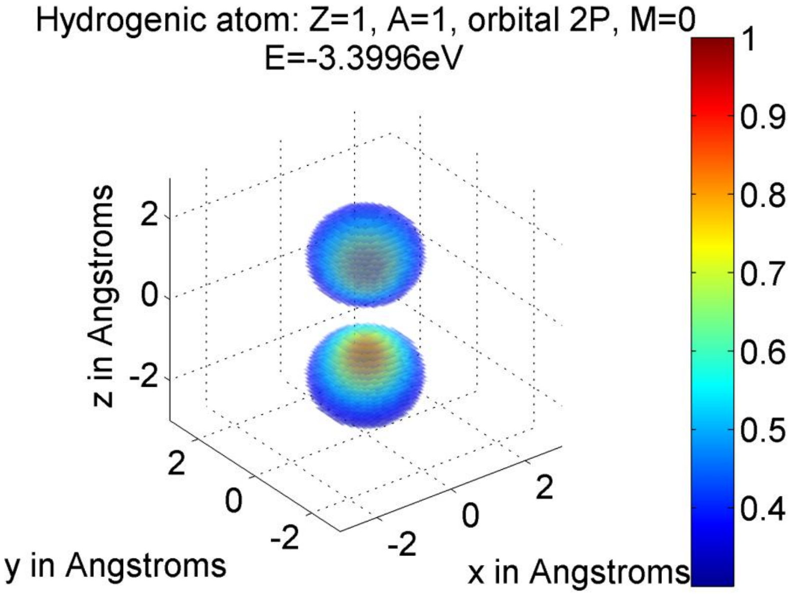
1Å = 10^{-10} m

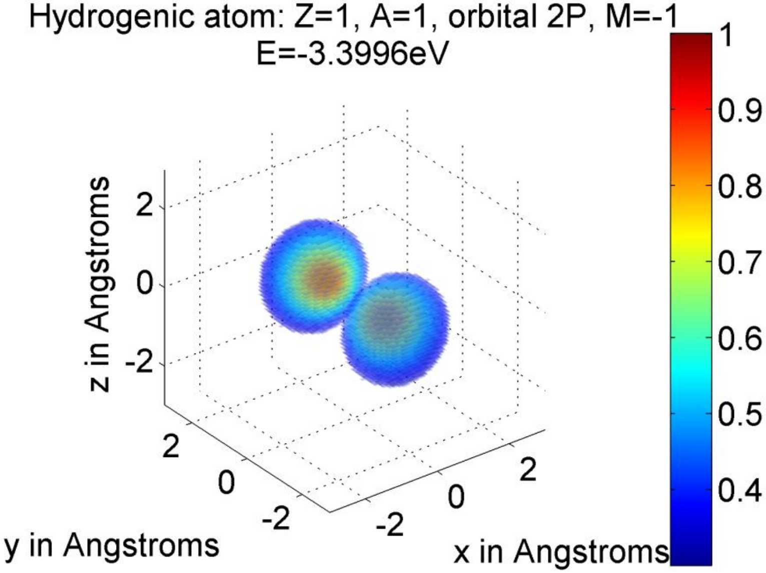
P

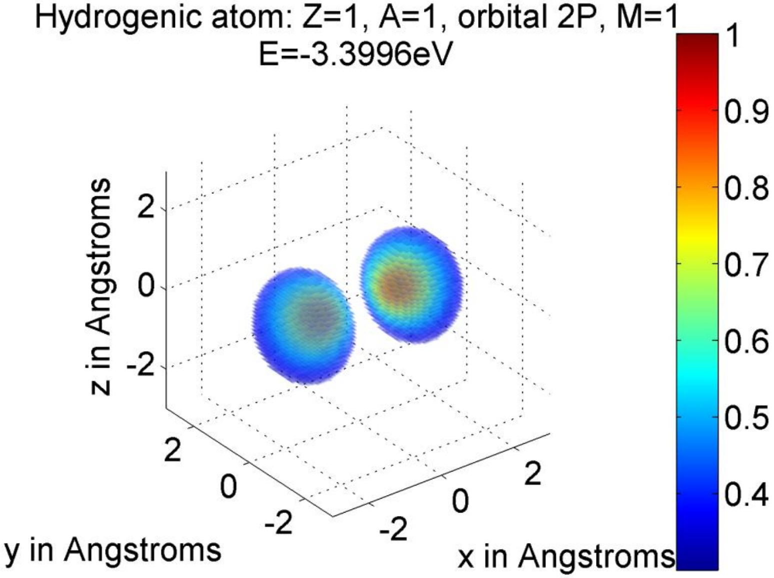
$n = 2, 3, 4, ...$

$l = 1$

$m = -1, 0, 1$





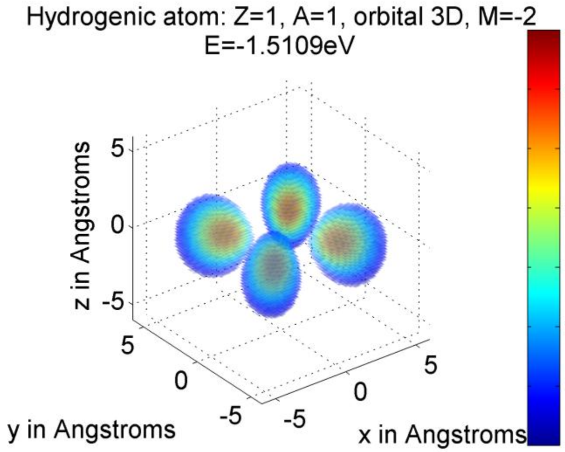


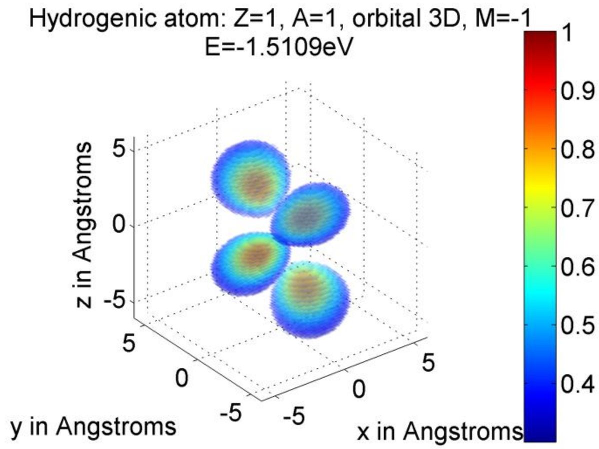
D

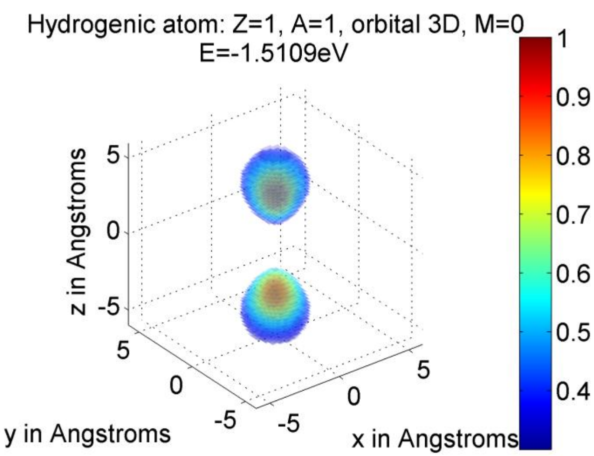
$n = 3, 4, 5, \ldots.$

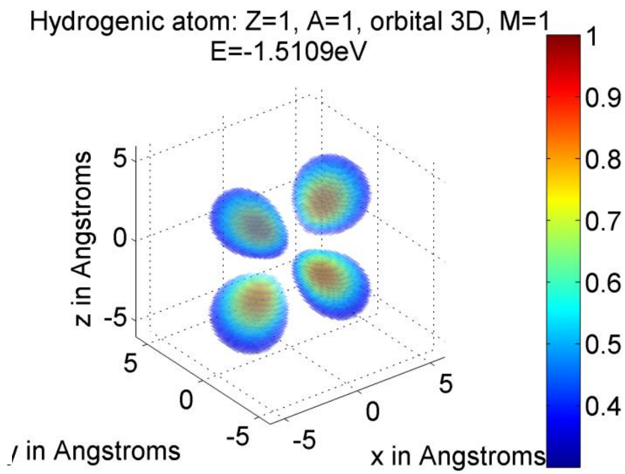
$l = 2$

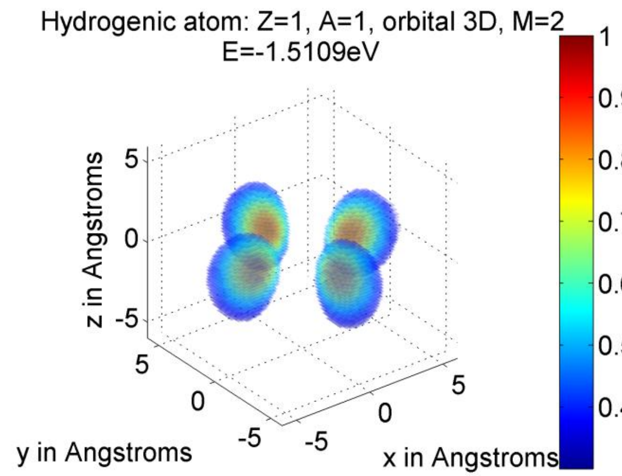
$m = -2, -1, 0, 1, 2$

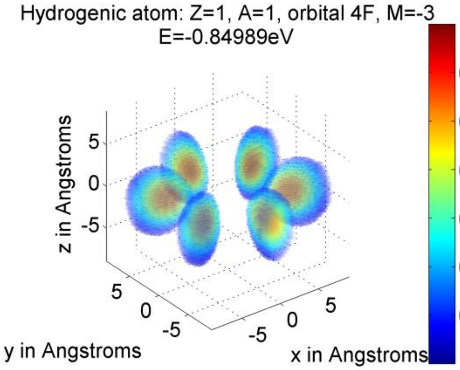


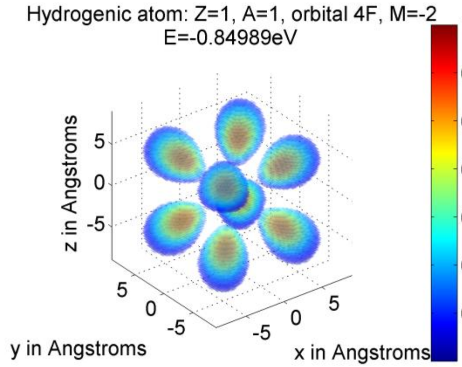


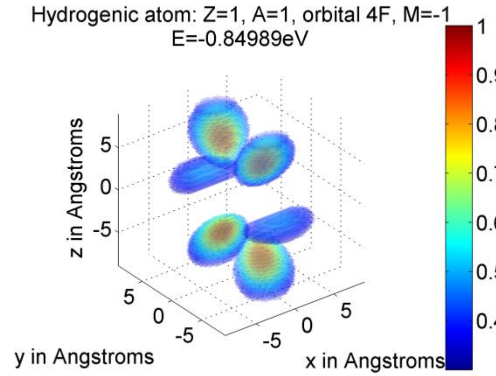


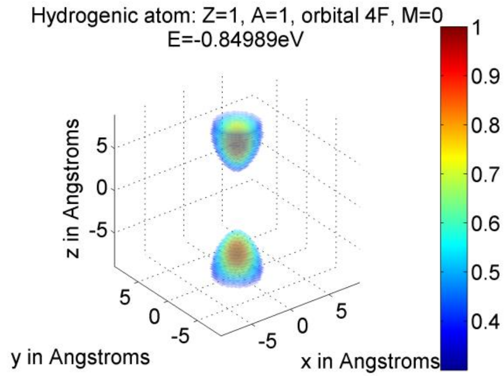


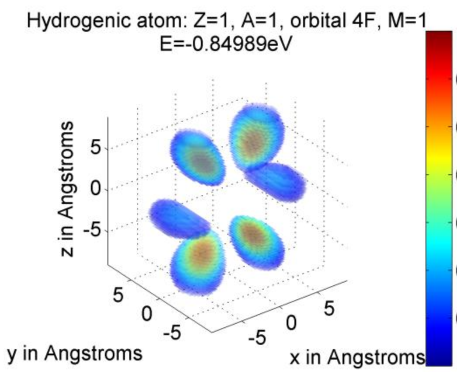


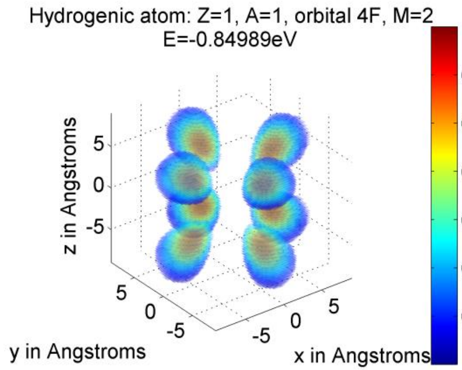


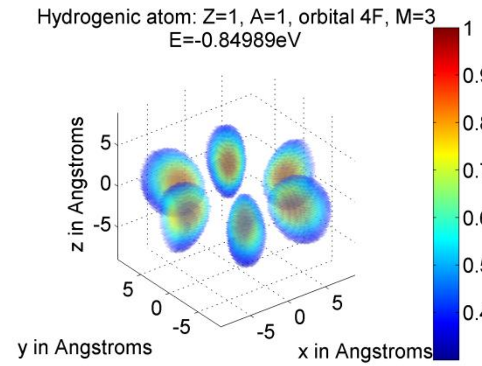




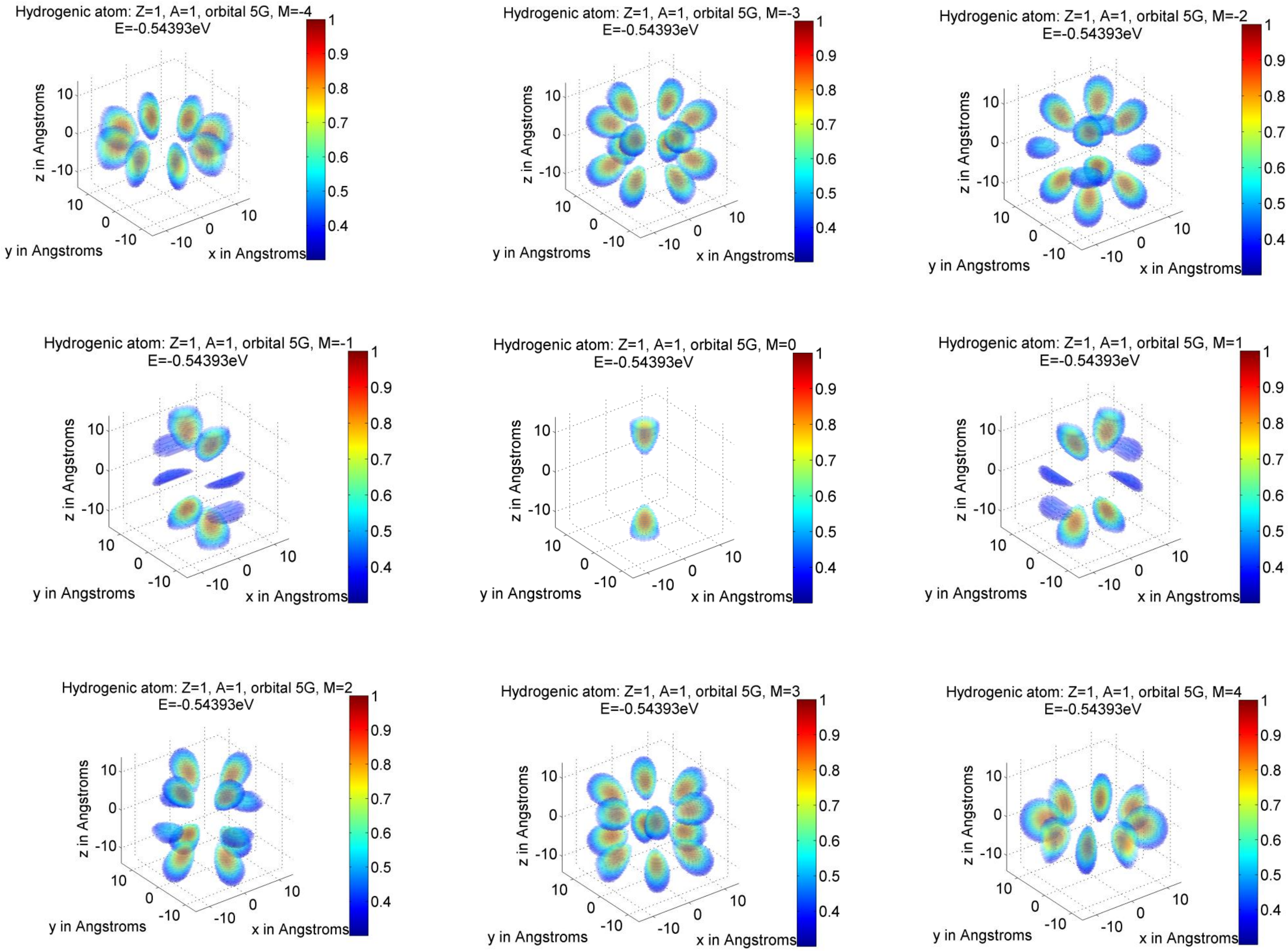








$$F \quad n=4,5,6,\ldots \quad l=3 \quad m=-3,-2,-1,0,1,2,3$$



$$G \qquad n = 5, 6, 7, ... \qquad l = 4 \qquad m = -4, -3, -2, -1, 0, 1, 2, 3, 4$$

Orbital transition rules

It turns out that only certain transitions between ‘hydrogenic’ orbitals are allowed in Quantum Mechanics

$$\Delta n \neq 0$$

$$\Delta l = \pm 1$$

$$\Delta m = 0 \quad \text{or} \quad \pm 1$$

Heisenberg Uncertainty Principle

$$\Delta x \Delta p \geq \frac{1}{2}\hbar$$

In other words, we have a *limit* upon how precisely we can measure **position** and **momentum** of a particle

$$\Delta E \Delta t \geq \frac{1}{2}\hbar$$

A similar relationship exists between **energy** and **time**

Werner Heisenberg 1901 – 1976

Not this one!

Electron orbital angular momentum and Spin

$$\mathbf{J} = \mathbf{L} + \mathbf{s}$$

Total angular momentum

$$|\mathbf{J}|^2 = j(j+1)\hbar^2$$

$$|\mathbf{L}|^2 = l(l+1)\hbar^2$$

$$|\mathbf{s}|^2 = s(s+1)\hbar^2$$

Magnitude of angular momenta

$$|l - s| \leq j \leq l + s$$

For example, in the z direction, the **quantization of angular momentum** means

$$L_z = m\hbar$$

$$m = -l, \ldots\ldots, l$$

$$s_z = k\hbar$$

$$k = -s, \ldots., s$$

Goudsmit & Uhlenbeck proposed in 1925 that the electron has 'intrinsic angular momentum' or spin. This is to account for the **anomalous Zeeman effect**, i.e. the extra splitting of spectral lines not predicted by previous quantum theories.

Spin 0 Neutral pions and kaons; α-particles.

Spin $\frac{1}{2}$ Electrons, positrons, protons, neutrons, electron neutrinos, muon neutrinos, muons, ...

Spin 1 ρ-meson; the photon (but it only has two possible projections $\hbar$ and $-\hbar$ in any direction because it has zero rest mass — these correspond to the two independent polarisations of light waves)

Spin $\frac{3}{2}$ Ω particles

Spin 2 The graviton, the quantum of gravitation

The **magnetic moment** of an electron therefore has **orbital** and **spin** components

$$\boldsymbol{\mu}_l = -\left(\frac{e}{2m_e}\right)\mathbf{L}$$

$$\boldsymbol{\mu}_s = -2\left(\frac{e}{2m_e}\right)\mathbf{s}$$

It turns out you get
twice as much for spin!

Quantized orbital angular
momentum and spin

$$L_z = m\hbar$$

$$m = -l, \ldots\ldots, l$$

$$s_z = k\hbar$$

$$k = -s, \ldots, s$$

i.e. assume
our measurement
direction is the z axis

If a magnetic field is applied
the electron changes in energy by

$$\Delta E = -\left(\boldsymbol{\mu}_l + \boldsymbol{\mu}_s\right)\cdot\mathbf{B}$$

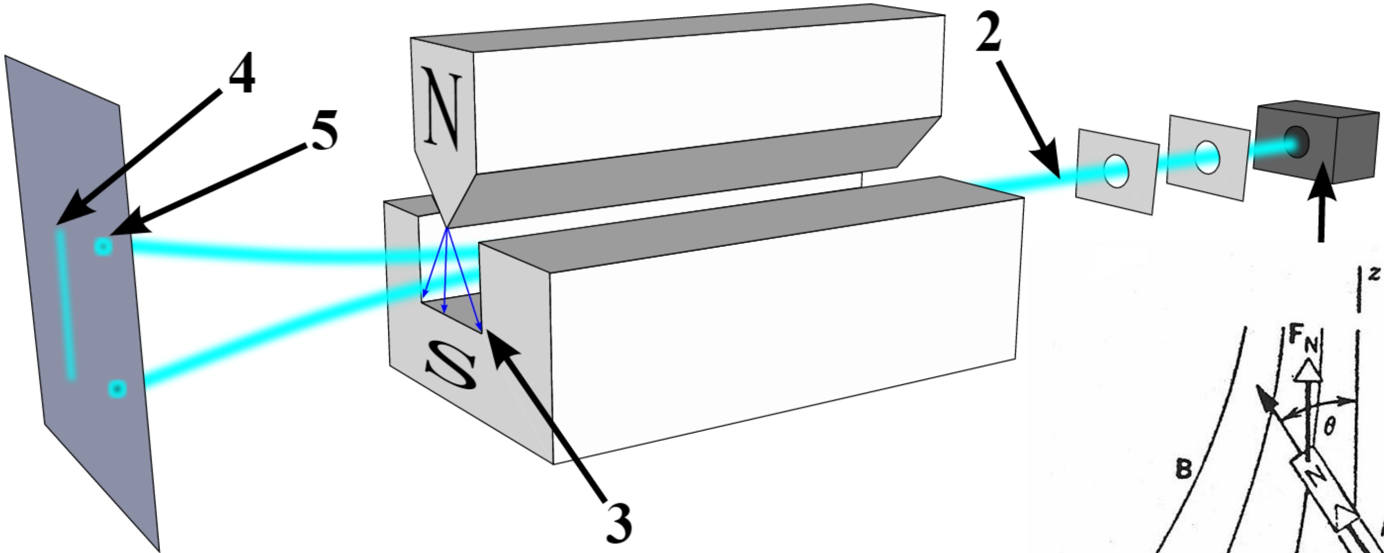
$$\boxed{\Delta E_{m,k} = -\frac{eB_z\hbar}{2m_e}\left(m + 2k\right)}$$

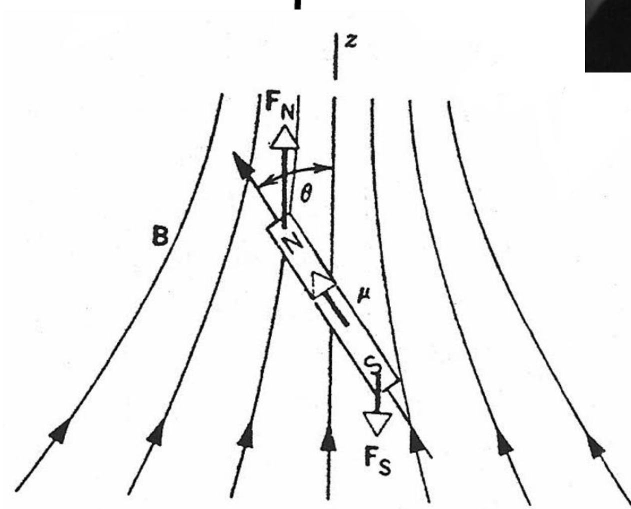
$$\Delta E = h\Delta f$$

Emmission spectrum
frequency shift resulting from
electron energy change

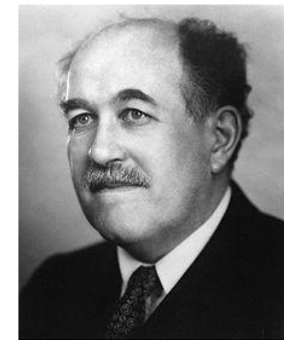
Since k = +1/2 or -1/2 for an electron
there will be *at least two* energy shifts
due to magnetic effects. An electron
with l > 0 will have more spectral lines
associated with different shifts

In 1922, **Stern & Gerlach** used a beam of **silver atoms** to investigate spin. There is only once ‘valence’ electron, which is in the 5s orbital. This has *no orbital angular momentum* i.e. l =0. Deflection of the beam via an *inhomogeneous* magnetic field is therefore only due to spin.





$$\mu_z = \mu \cos\theta$$


Otto Stern
1888-1969


Walther
Gerlach
1889-1979

Silver atoms travel through an *inhomogeneous* magnetic field and are deflected up or down depending on their spin

$$\boldsymbol{\mu}_s = -2\left(\frac{e}{2m_e}\right)\mathbf{s}$$

$$\mathbf{s}\cdot\hat{\mathbf{z}} = -\tfrac{1}{2}\hbar, \tfrac{1}{2}\hbar$$

$$\boxed{\mu_z = -\tfrac{1}{2}\frac{e\hbar}{m_e}, \tfrac{1}{2}\frac{e\hbar}{m_e}}$$

$$F = \mu_z \frac{\partial B_z}{\partial z}$$

THE COPENHAGEN INTERPRETATION

The Copenhagen Interpretation of Quantum Mechanics
(Bohr, Heisenberg, Born et al 1925-1927)

"Physical systems generally do not have definite properties prior to being measured, and quantum mechanics can only predict the **probabilities** that measurements will produce certain results.

$$|\psi|^2$$

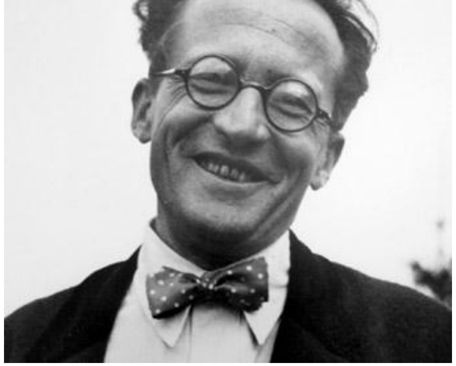
The act of measurement affects the system, causing the set of probabilities to reduce to only one of the possible values immediately after the measurement. This feature is known as wavefunction collapse."

An electron therefore has a wavefunction which incorporates *both* spin states, until it is measured.

An electron in a hydrogen atom has wavefunction which is a *superposition of all possible quantum numbers*. Only when you measure it, does it collapse to one particular 'eigenstate.'

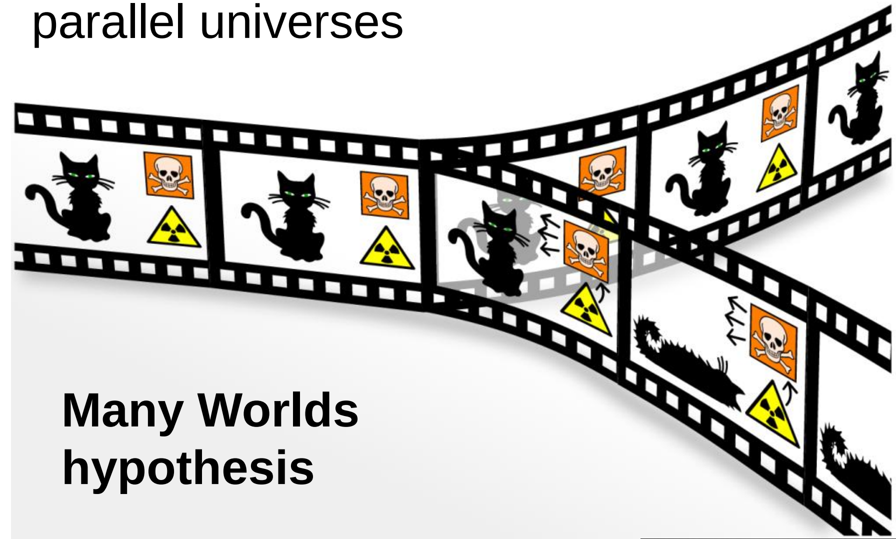
https://en.wikipedia.org/wiki/Copenhagen_interpretation

David Bohm
1917-1992



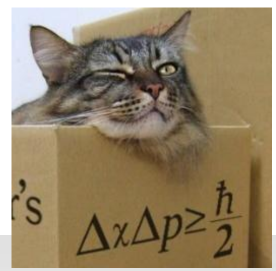
Erwin Schrödinger
1887-1961

All possible outcomes are realized in parallel universes

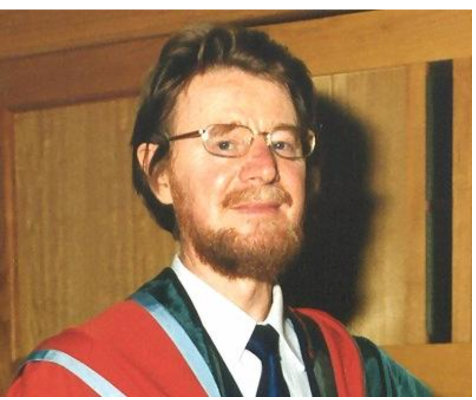


Many Worlds hypothesis

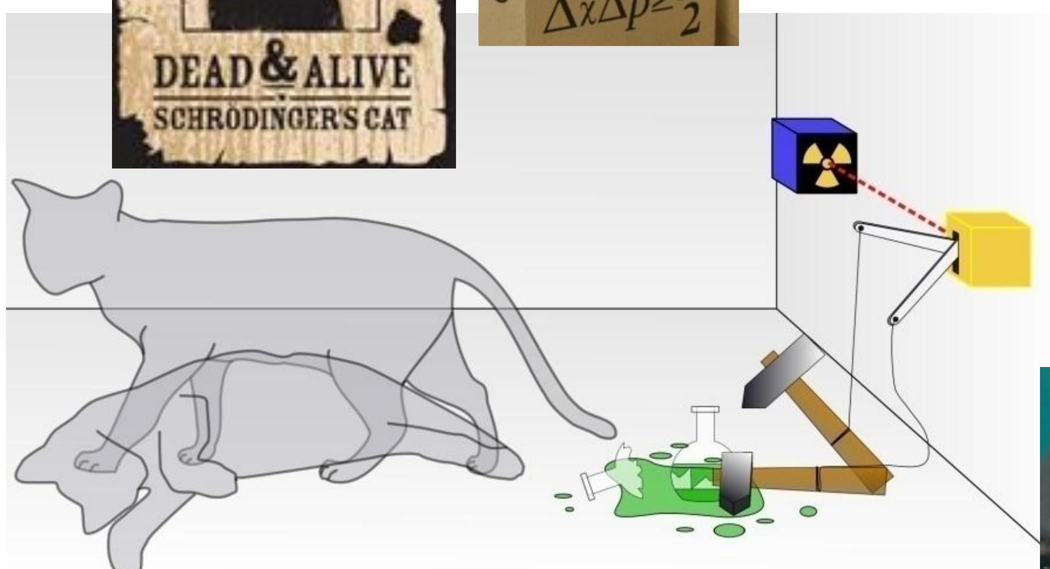
'Pilot waves'
Hidden variables

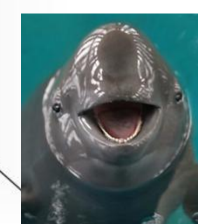


Hugh Everett
1930-1982



John Bell
1928-1990

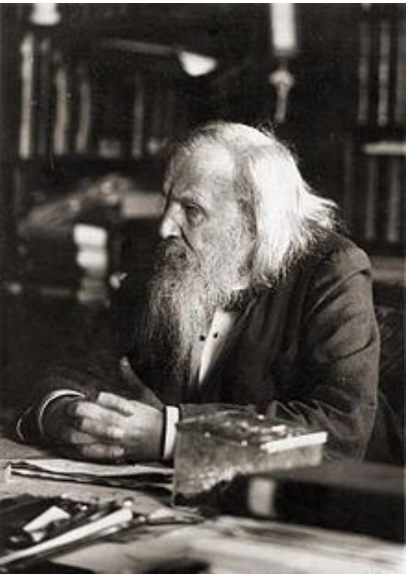




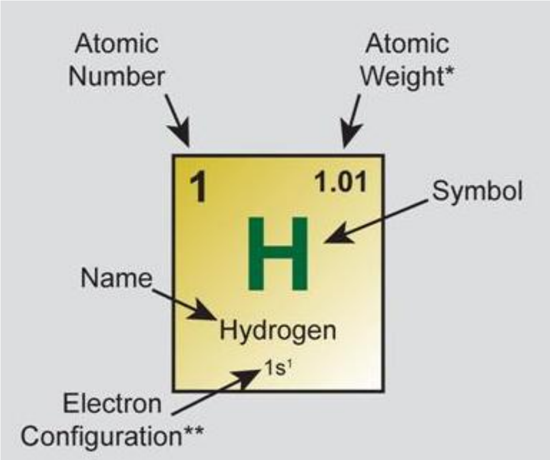
Poor
puss!

EXPLAINING CHEMISTRY

Dmitri Mendeleev
1834-1907



1s
2s 2p
3s 3p 3d
4s 4p 4d 4f
5s 5p 5d 5f ...
6s 6p 6d ... ...



Wolfgang Pauli
1900 – 1958

Periodic Table of the Elements

Period	Group 1 Ia	2 IIa	3 IIIb	4 IVb	5 Vb	6 VIb	7 VIIb	8	9 ← VIIIb →	10	11 Ib	12 IIb	13 IIIa	14 IVa	15 Va	16 VIa	17 VIIa	18 0
1	1 1.01 **H** Hydrogen $1s^{1}$																	2 4.00 **He** Helium $1s^{2}$
2	3 6.94 **Li** Lithium $1s^{2}2s^{1}$	4 9.01 **Be** Beryllium $1s^{2}2s^{2}$											5 10.81 **B** Boron $1s^{2}2s^{2}p^{1}$	6 12.01 **C** Carbon $1s^{2}2s^{2}p^{2}$	7 14.01 **N** Nitrogen $1s^{2}2s^{2}p^{3}$	8 16.00 **O** Oxygen $1s^{2}2s^{2}p^{4}$	9 19.00 **F** Fluorine $1s^{2}2s^{2}p^{5}$	10 20.18 **Ne** Neon $1s^{2}2s^{2}p^{6}$
3	11 22.99 **Na** Sodium $[Ne]3s^{1}$	12 24.31 **Mg** Magnesium $[Ne]3s^{2}$											13 26.98 **Al** Aluminum $[Ne]3s^{2}p^{1}$	14 28.09 **Si** Silicon $[Ne]3s^{2}p^{2}$	15 30.97 **P** Phosphorus $[Ne]3s^{2}p^{3}$	16 32.07 **S** Sulfur $[Ne]3s^{2}p^{4}$	17 35.45 **Cl** Chlorine $[Ne]3s^{2}p^{5}$	18 39.95 **Ar** Argon $[Ne]3s^{2}p^{6}$
4	19 39.10 **K** Potassium $[Ar]4s^{1}$	20 40.08 **Ca** Calcium $[Ar]4s^{2}$	21 44.96 **Sc** Scandium $[Ar]3d^{1}4s^{2}$	22 47.87 **Ti** Titanium $[Ar]3d^{2}4s^{2}$	23 50.94 **V** Vanadium $[Ar]3d^{3}4s^{2}$	24 52.00 **Cr** Chromium $[Ar]3d^{5}4s^{1}$	25 54.94 **Mn** Manganese $[Ar]3d^{5}4s^{2}$	26 55.85 **Fe** Iron $[Ar]3d^{6}4s^{2}$	27 58.93 **Co** Cobalt $[Ar]3d^{7}4s^{2}$	28 58.69 **Ni** Nickel $[Ar]3d^{8}4s^{2}$	29 63.55 **Cu** Copper $[Ar]3d^{10}4s^{1}$	30 65.39 **Zn** Zinc $[Ar]3d^{10}4s^{2}$	31 69.72 **Ga** Gallium $[Ar]3d^{10}4s^{2}p^{1}$	32 72.61 **Ge** Germanium $[Ar]3d^{10}4s^{2}p^{2}$	33 74.92 **As** Arsenic $[Ar]3d^{10}4s^{2}p^{3}$	34 78.96 **Se** Selenium $[Ar]3d^{10}4s^{2}p^{4}$	35 79.90 **Br** Bromine $[Ar]3d^{10}4s^{2}p^{5}$	36 83.80 **Kr** Krypton $[Ar]3d^{10}4s^{2}p^{6}$
5	37 85.47 **Rb** Rubidium $[Kr]5s^{1}$	38 87.62 **Sr** Strontium $[Kr]5s^{2}$	39 88.91 **Y** Yttrium $[Kr]4d^{1}5s^{2}$	40 91.22 **Zr** Zirconium $[Kr]4d^{2}5s^{2}$	41 92.91 **Nb** Niobium $[Kr]4d^{4}5s^{1}$	42 95.94 **Mo** Molybdenum $[Kr]4d^{5}5s^{1}$	43 (98) **Tc** Technetium $[Kr]4d^{5}5s^{2}$	44 101.07 **Ru** Ruthenium $[Kr]4d^{7}5s^{1}$	45 102.91 **Rh** Rhodium $[Kr]4d^{8}5s^{1}$	46 106.42 **Pd** Palladium $[Kr]4d^{10}$	47 107.87 **Ag** Silver $[Kr]4d^{10}5s^{1}$	48 112.41 **Cd** Cadmium $[Kr]4d^{10}5s^{2}$	49 114.82 **In** Indium $[Kr]4d^{10}5s^{2}p^{1}$	50 118.71 **Sn** Tin $[Kr]4d^{10}5s^{2}p^{2}$	51 121.76 **Sb** Antimony $[Kr]4d^{10}5s^{2}p^{3}$	52 127.60 **Te** Tellurium $[Kr]4d^{10}5s^{2}p^{4}$	53 126.90 **I** Iodine $[Kr]4d^{10}5s^{2}p^{5}$	54 131.29 **Xe** Xenon $[Kr]4d^{10}5s^{2}p^{6}$
6	55 132.91 **Cs** Cesium $[Xe]6s^{1}$	56 137.33 **Ba** Barium $[Xe]6s^{2}$	♦	72 178.49 **Hf** Hafnium $[Xe]4f^{14}5d^{2}6s^{2}$	73 180.95 **Ta** Tantalum $[Xe]4f^{14}5d^{3}6s^{2}$	74 183.84 **W** Tungsten $[Xe]4f^{14}5d^{4}6s^{2}$	75 186.21 **Re** Rhenium $[Xe]4f^{14}5d^{5}6s^{2}$	76 190.23 **Os** Osmium $[Xe]4f^{14}5d^{6}6s^{2}$	77 192.22 **Ir** Iridium $[Xe]4f^{14}5d^{7}6s^{2}$	78 195.08 **Pt** Platinum $[Xe]4f^{14}5d^{9}6s^{1}$	79 196.97 **Au** Gold $[Xe]4f^{14}5d^{10}6s^{1}$	80 200.59 **Hg** Mercury $[Xe]4f^{14}5d^{10}6s^{2}$	81 204.38 **Tl** Thallium $[Xe]4f^{14}5d^{10}6s^{2}p^{1}$	82 207.20 **Pb** Lead $[Xe]4f^{14}5d^{10}6s^{2}p^{2}$	83 208.98 **Bi** Bismuth $[Xe]4f^{14}5d^{10}6s^{2}p^{3}$	84 (209) **Po** Polonium $[Xe]4f^{14}5d^{10}6s^{2}p^{4}$	85 (210) **At** Astatine $[Xe]4f^{14}5d^{10}6s^{2}p^{5}$	86 (222) **Rn** Radon $[Xe]4f^{14}5d^{10}6s^{2}p^{6}$
7	87 (223) **Fr** Francium $[Rn]7s^{1}$	88 (226) **Ra** Radium $[Rn]7s^{2}$	★	104 (265) **Rf** Rutherfordium $[Rn]5f^{14}6d^{2}7s^{2}$	105 (268) **Db** Dubnium $[Rn]5f^{14}6d^{3}7s^{2}$	106 (271) **Sg** Seaborgium $[Rn]5f^{14}6d^{4}7s^{2}$	107 (270) **Bh** Bohrium $[Rn]5f^{14}6d^{5}7s^{2}$	108 (277) **Hs** Hassium $[Rn]5f^{14}6d^{6}7s^{2}$	109 (276) **Mt** Meitnerium $[Rn]5f^{14}6d^{7}7s^{2}$	110 (281) **Ds** Darmstadtium $[Rn]5f^{14}6d^{9}7s^{1}$	111 (280) **Rg** Roentgenium $[Rn]5f^{14}6d^{9}7s^{2}$	112 (285) **Cn** Copernicium $[Rn]5f^{14}6d^{10}7s^{2}$	113 (284) **Uut** Ununtrium $[Rn]5f^{14}6d^{10}7s^{2}7p^{1}$	114 (289) **Fl** Flerovium $[Rn]5f^{14}6d^{10}7s^{2}7p^{2}$	115 (288) **Uup** Ununpentium $[Rn]5f^{14}6d^{10}7s^{2}7p^{3}$	116 (293) **Lv** Livermorium $[Rn]5f^{14}6d^{10}7s^{2}7p^{4}$	117 (294) **Uus** Ununseptium $[Rn]5f^{14}6d^{10}7s^{2}7p^{5}$	118 (294) **Uuo** Ununoctium $[Rn]5f^{14}6d^{10}7s^{2}7p^{6}$

♦	57 138.91 **La** Lanthanum $[Xe]5d^{1}6s^{2}$	58 140.12 **Ce** Cerium $[Xe]4f^{1}5d^{1}6s^{2}$	59 140.91 **Pr** Praseodymium $[Xe]4f^{3}6s^{2}$	60 144.24 **Nd** Neodymium $[Xe]4f^{4}6s^{2}$	61 (145) **Pm** Promethium $[Xe]4f^{5}6s^{2}$	62 150.36 **Sm** Samarium $[Xe]4f^{6}6s^{2}$	63 151.96 **Eu** Europium $[Xe]4f^{7}6s^{2}$	64 157.25 **Gd** Gadolinium $[Xe]4f^{7}5d^{1}6s^{2}$	65 158.93 **Tb** Terbium $[Xe]4f^{9}6s^{2}$	66 162.50 **Dy** Dysprosium $[Xe]4f^{10}6s^{2}$	67 164.93 **Ho** Holmium $[Xe]4f^{11}6s^{2}$	68 167.26 **Er** Erbium $[Xe]4f^{12}6s^{2}$	69 168.93 **Tm** Thulium $[Xe]4f^{13}6s^{2}$	70 173.04 **Yb** Ytterbium $[Xe]4f^{14}6s^{2}$	71 174.97 **Lu** Lutetium $[Xe]4f^{14}5d^{1}6s^{2}$
★	89 (227) **Ac** Actinium $[Rn]6d^{1}7s^{2}$	90 232.04 **Th** Thorium $[Rn]6d^{2}7s^{2}$	91 231.04 **Pa** Protactinium $[Rn]5f^{2}6d^{1}7s^{2}$	92 238.03 **U** Uranium $[Rn]5f^{3}6d^{1}7s^{2}$	93 (237) **Np** Neptunium $[Rn]5f^{4}6d^{1}7s^{2}$	94 (244) **Pu** Plutonium $[Rn]5f^{6}7s^{2}$	95 (243) **Am** Americium $[Rn]5f^{7}7s^{2}$	96 (247) **Cm** Curium $[Rn]5f^{7}6d^{1}7s^{2}$	97 (247) **Bk** Berkelium $[Rn]5f^{9}7s^{2}$	98 (251) **Cf** Californium $[Rn]5f^{10}7s^{2}$	99 (252) **Es** Einsteinium $[Rn]5f^{11}7s^{2}$	100 (257) **Fm** Fermium $[Rn]5f^{12}7s^{2}$	101 (258) **Md** Mendelevium $[Rn]5f^{13}7s^{2}$	102 (259) **No** Nobelium $[Rn]5f^{14}7s^{2}$	103 (262) **Lr** Lawrencium $[Rn]5f^{14}7s^{2}7p^{1}$

Alkali Metals
Alkaline Earth Metals
Transition Metals
Non-metals
Lanthanide Series
Actinide Series
Halogens
Inert Gases
Other Metals

Atomic Number — Atomic Weight* — Symbol — Name — Electron Configuration**

1 1.01 **H** Hydrogen $1s^{1}$

Aa - Solid
Aa - Gas
Aa - Liquid
Aa - Synthetically Prepared

* Based on Carbon-12. (###) represents most stable or most stable expected isotope.
** Some electron configurations are based on theoretical expected arrangements.

Innovating Science™ by Aldon Corporation

"cutting edge science for the classroom"

Wolfgang Pauli
1900 – 1958

Pauli Exclusion principle

Two identical fermions (i.e. particle with half integer spin such as electrons, protons, neutrons and neutrinos) cannot exist in the same quantum state simultaneously.

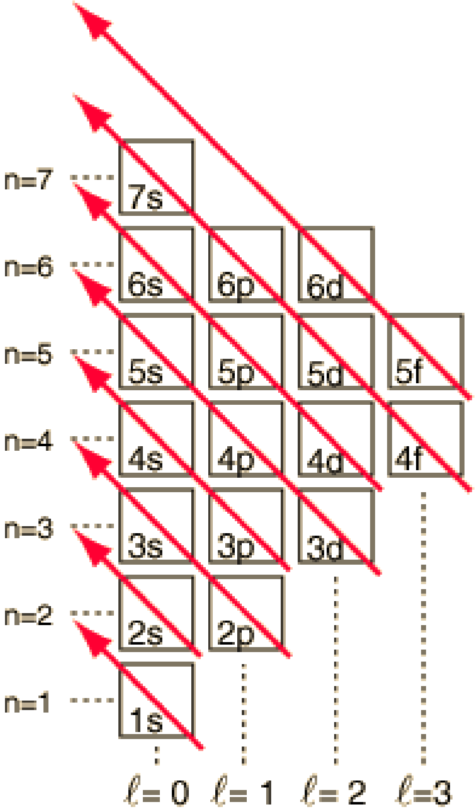
For each n,l,m orbital of a Hydrogenic atom
we can have two possible electrons, since the spin quantum number of an electron is +1/2 or -1/2

This helps to explain the structure of the periodic table.
i.e. we fill up quantum orbitals using the electrons contained within a particular element.

‘Unfilled’ orbitals give rise to chemical activity of an element.
i.e. Hydrogen will preferentially ‘lose’ its single electron to Oxygen. Oxygen can ‘accept’ two electrons, which is why water H_2O is a stable molecule.

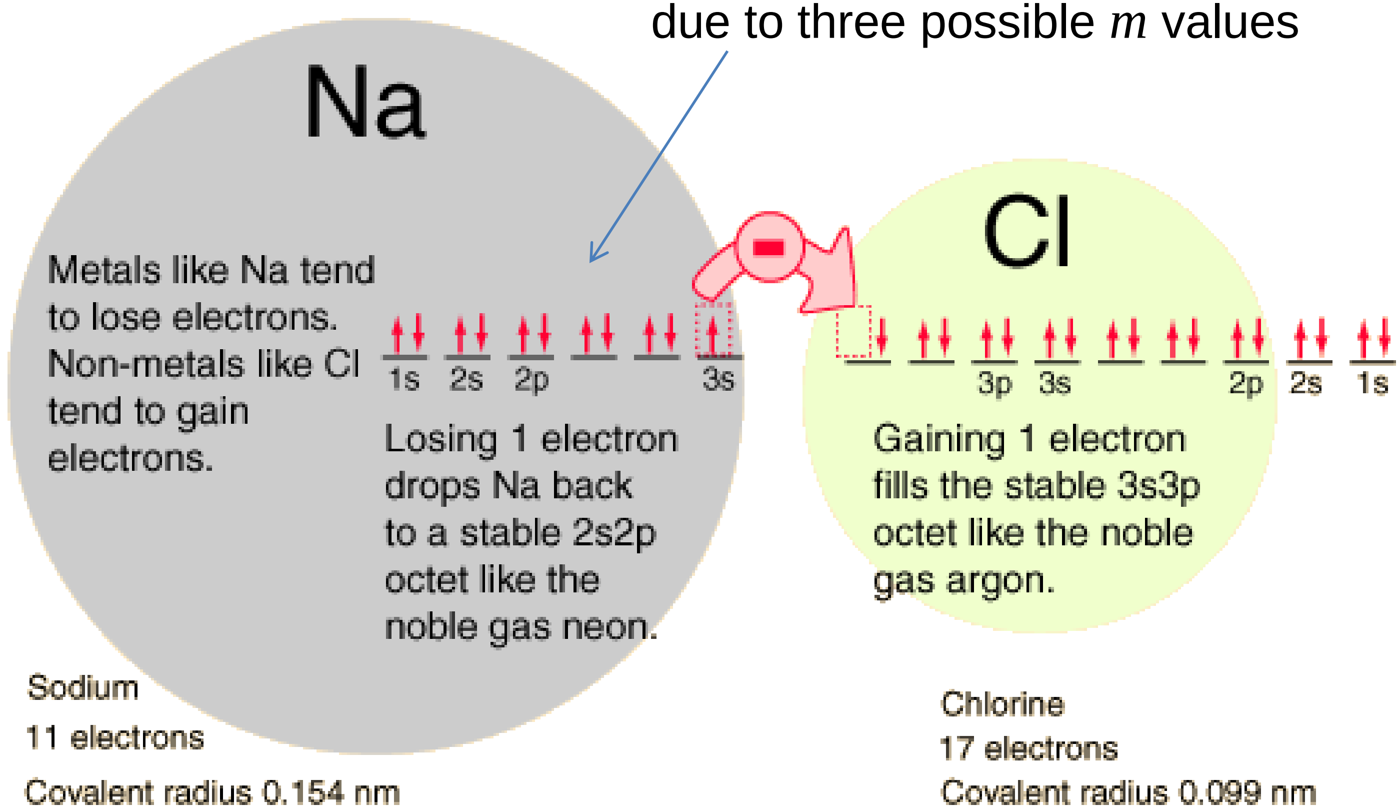
1s
2s 2p
3s 3p 3d
4s 4p 4d 4f
5s 5p 5d 5f …
6s 6p 6d … … …

Aufbau (“atomic building up”) or
Madelung principle



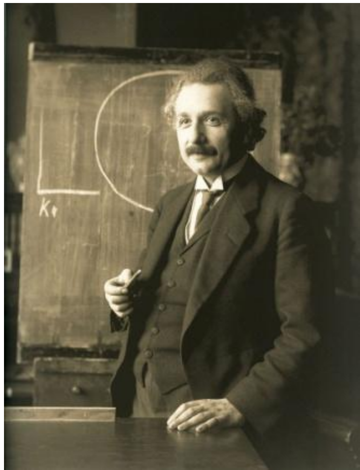
S	P	D
$n = 1, 2, 3, \ldots$	$n = 2, 3, 4, \ldots.$	$n = 3, 4, 5, \ldots.$
$l = 0$	$l = 1$	$l = 2$
$m = 0$	$m = -1, 0, 1$	$m = -2, -1, 0, 1, 2$

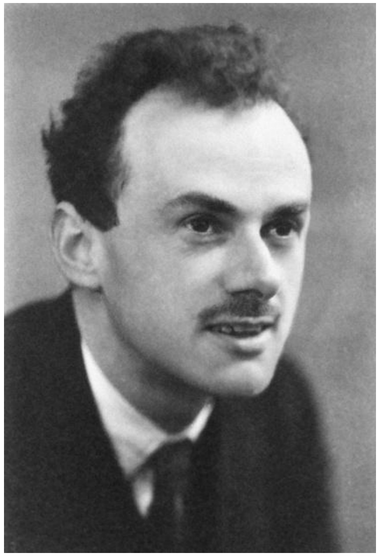
i.e. three possible 2P orbitals
due to three possible *m* values



http://hyperphysics.phy-astr.gsu.edu/hbase/chemical/eleorb.html

APPLYING RELATIVITY TO QUANTUM THEORY





Paul Dirac
1902 – 1984
Nobel Prize 1933

$$E_n = -\frac{m_e e^4 Z^2}{8\varepsilon_0^2 h^2 n^2} = -\frac{m_e c^2 Z^2}{2n^2}\frac{e^4}{4\varepsilon_0^2 h^2 c^2}$$

$$\alpha = \frac{e^2}{4\pi\varepsilon_0 \hbar c} = \frac{e^2}{2\varepsilon_0 hc} \approx \frac{1}{137}$$

$$\alpha^2 = \frac{e^4}{4\varepsilon_0^2 h^2 c^2}$$

$$E_n = -\frac{m_e c^2 Z^2}{2n^2}\alpha^2$$

Non-relativistic orbital energies of electrons in a Hydrogenic atom

Arnold Sommerfeld
1868-1951

Schrödinger equation including Special Relativity, for spin ½ particles

Electron energies predicted using the **Dirac Equation**

$$E = -m_e c^2\left[1-\left(1+\left(\frac{Z\alpha}{n-j-\frac{1}{2}+\sqrt{(j+\frac{1}{2})^2 - Z^2\alpha^2}}\right)^2\right)^{-1/2}\right]$$

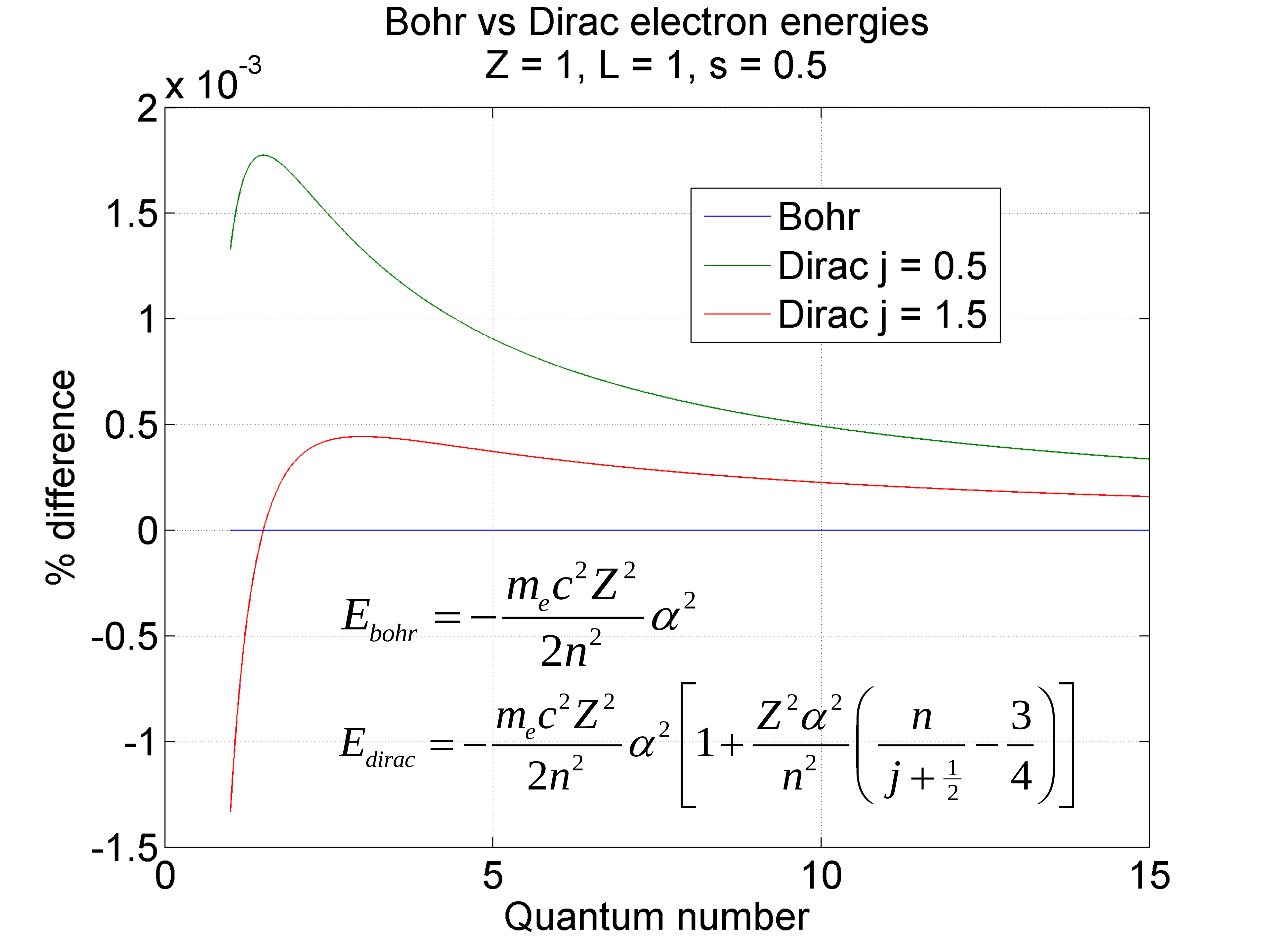
$$E \approx -\frac{m_e c^2 Z^2}{2n^2}\alpha^2\left[1+\frac{Z^2\alpha^2}{n^2}\left(\frac{n}{j+\frac{1}{2}}-\frac{3}{4}\right)\right]$$

Total angular momentum quantum number *j* $\quad |l-s| \le j \le l+s$

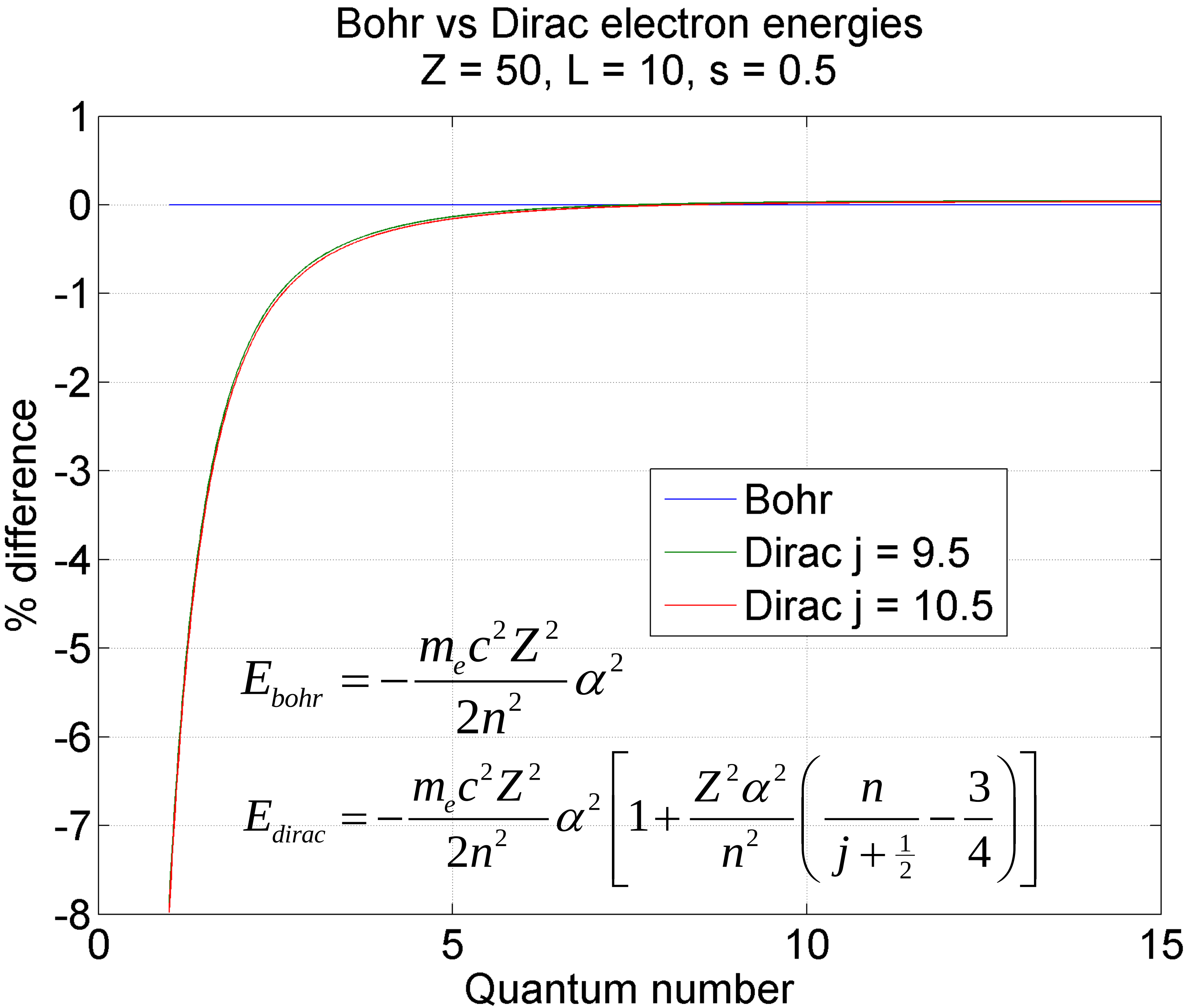
Sommerfeld derived a very similar formula by considering the relativistic form of kinetic energy

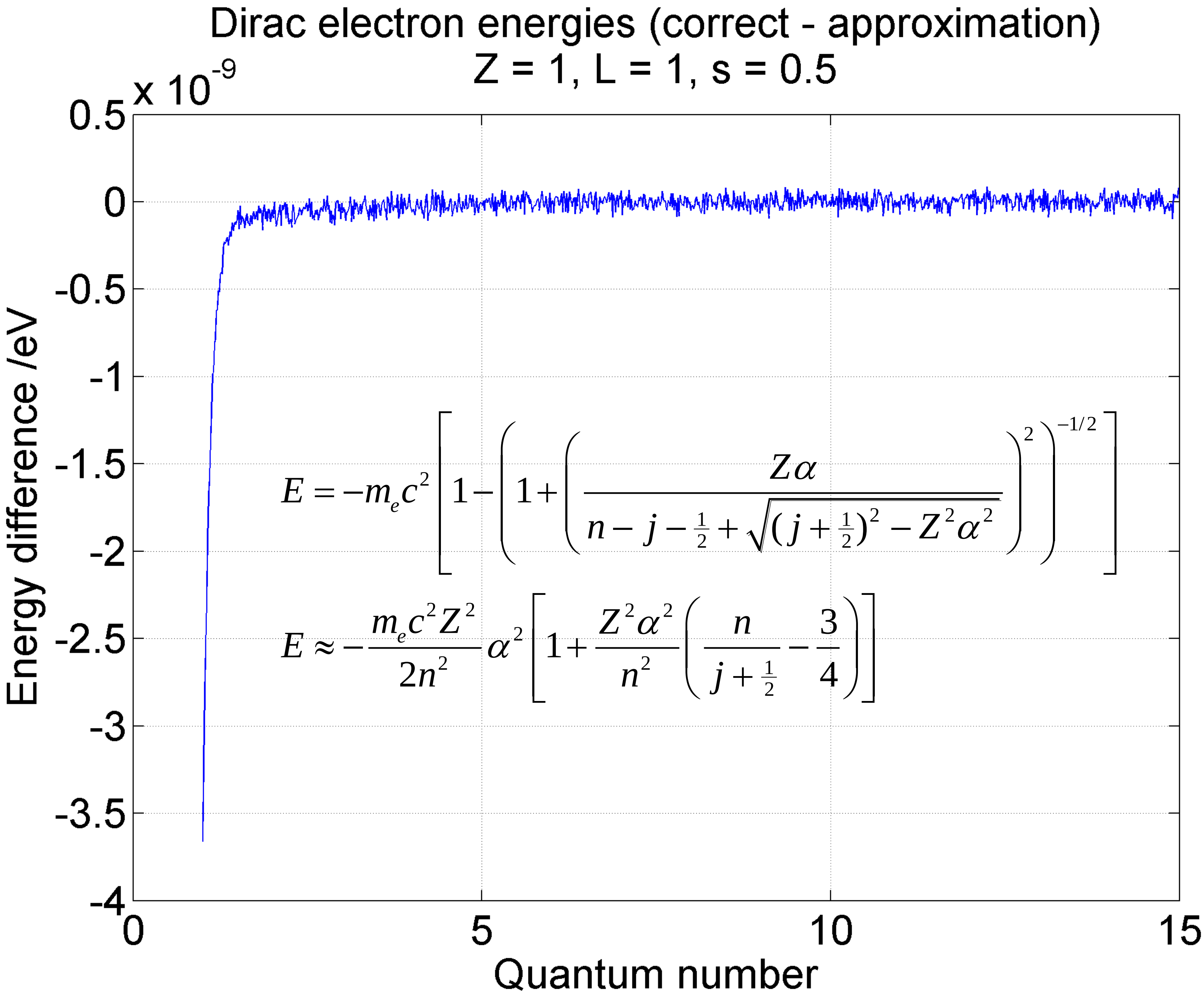
$$E_{KE} = (\gamma - 1) m_e c^2$$

$$\gamma = \left(1-\frac{v^2}{c^2}\right)^{-1/2}$$

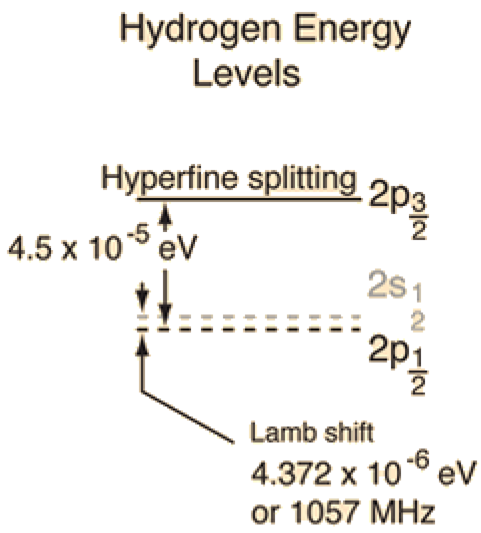


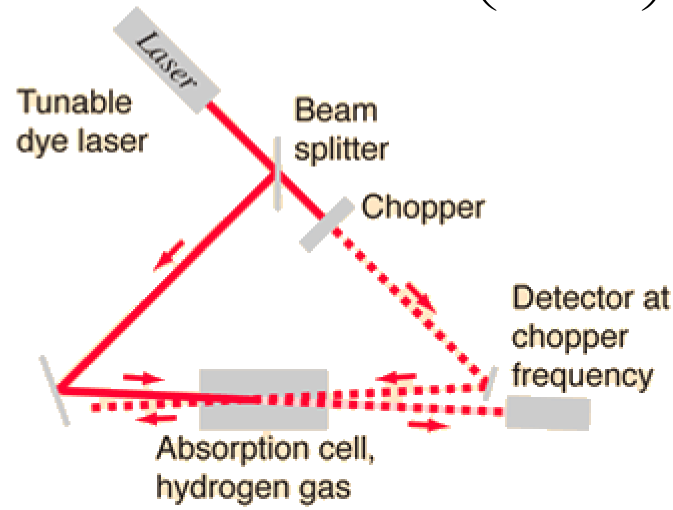
Bohr vs Dirac electron energies
Z = 1, L = 1, s = 0.5
x 10^-3
2
1.5
1
0.5
0
-0.5
-1
-1.5
0
5
10
15
% difference
Quantum number
Bohr
Dirac j = 0.5
Dirac j = 1.5
$E_{bohr} = -\frac{m_e c^2 Z^2}{2n^2}\alpha^2$
$E_{dirac} = -\frac{m_e c^2 Z^2}{2n^2}\alpha^2\left[1+\frac{Z^2\alpha^2}{n^2}\left(\frac{n}{j+\frac{1}{2}}-\frac{3}{4}\right)\right]$


Bohr vs Dirac electron energies
Z = 50, L = 10, s = 0.5
% difference
Quantum number
Bohr
Dirac j = 9.5
Dirac j = 10.5
$E_{bohr} = -\frac{m_e c^2 Z^2}{2n^2}\alpha^2$
$E_{dirac} = -\frac{m_e c^2 Z^2}{2n^2}\alpha^2\left[1+\frac{Z^2\alpha^2}{n^2}\left(\frac{n}{j+\frac{1}{2}}-\frac{3}{4}\right)\right]$


Dirac electron energies (correct - approximation)
Z = 1, L = 1, s = 0.5
x 10^-9
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
0
5
10
15
Energy difference /eV
Quantum number
$E = -m_e c^2 \left[1 - \left(1 + \left(\frac{Z\alpha}{n - j - \frac{1}{2} + \sqrt{(j+\frac{1}{2})^2 - Z^2\alpha^2}} \right)^2 \right)^{-1/2} \right]$
$E \approx -\frac{m_e c^2 Z^2}{2n^2} \alpha^2 \left[1 + \frac{Z^2\alpha^2}{n^2} \left(\frac{n}{j+\frac{1}{2}} - \frac{3}{4} \right) \right]$

$$\Delta f \approx \frac{\alpha^5 m_e c^2}{6\pi h} \ln\left(\frac{4\varepsilon_0 \hbar c}{e^2}\right) = 1057\mathrm{MHz}$$





Willis Lamb
1913-2008

But even the Dirac equation could not predict the **Lamb Shift**

This required Quantum Electrodyamics (QED)

$$E = -m_e c^2 \left[1 - \left(1 + \left(\frac{Z\alpha}{n - j - \frac{1}{2} + \sqrt{(j+\frac{1}{2})^2 - Z^2\alpha^2}} \right)^2 \right)^{-1/2} \right]$$

$$|l - s| \le j \le l + s$$

$$E \approx -\frac{m_e c^2 Z^2}{2n^2}\alpha^2 \left[1 + \frac{Z^2\alpha^2}{n^2}\left(\frac{n}{j+\frac{1}{2}} - \frac{3}{4} \right) \right]$$

Electron (kinetic + potential) energies predicted using the **Dirac Equation**

TOWARDS THE STANDARD MODEL

Hans Bethe
1906 – 2005
Nobel Prize 1967

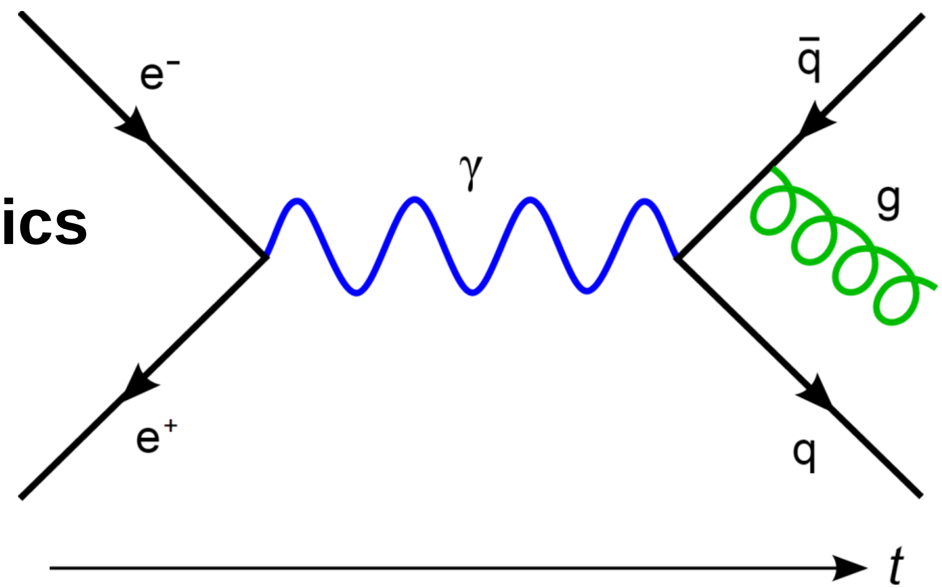
Sin-Itiro Tomonaga
1906-1979
Nobel prize 1965

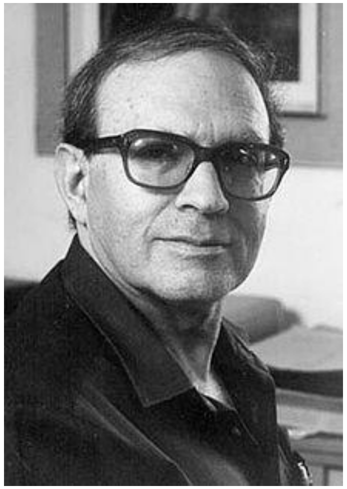
Richard Feynman
1918-1988
Nobel Prize 1965

Julian Schwinger
1918-1994
Nobel Prize 1965

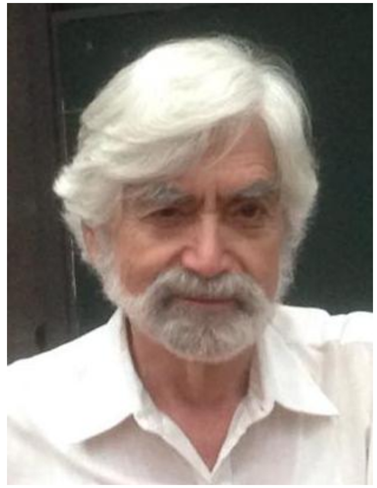
Freeman Dyson
(X, 1936-1941)
1923-

Quantum Electro-Dynamics (QED)



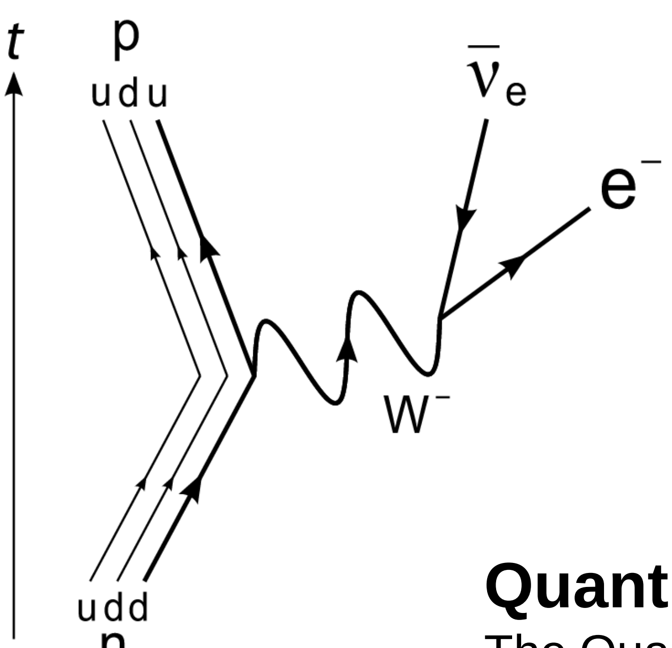


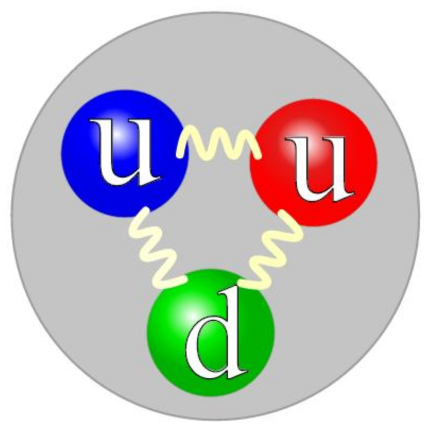
Yuval Ne'eman
1925-2006



George Zweig
1937-

Murray Gell-Mann
1929-

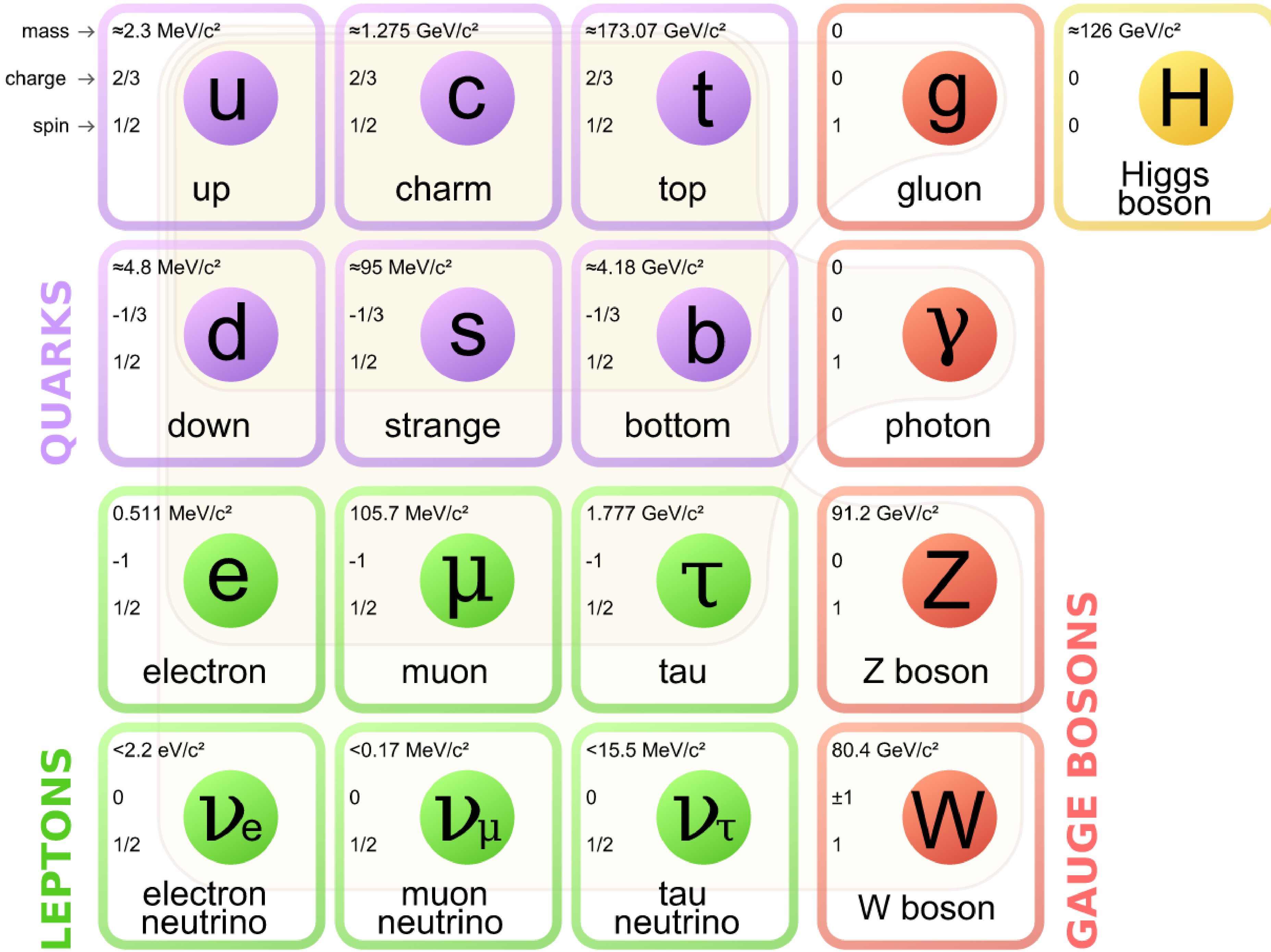




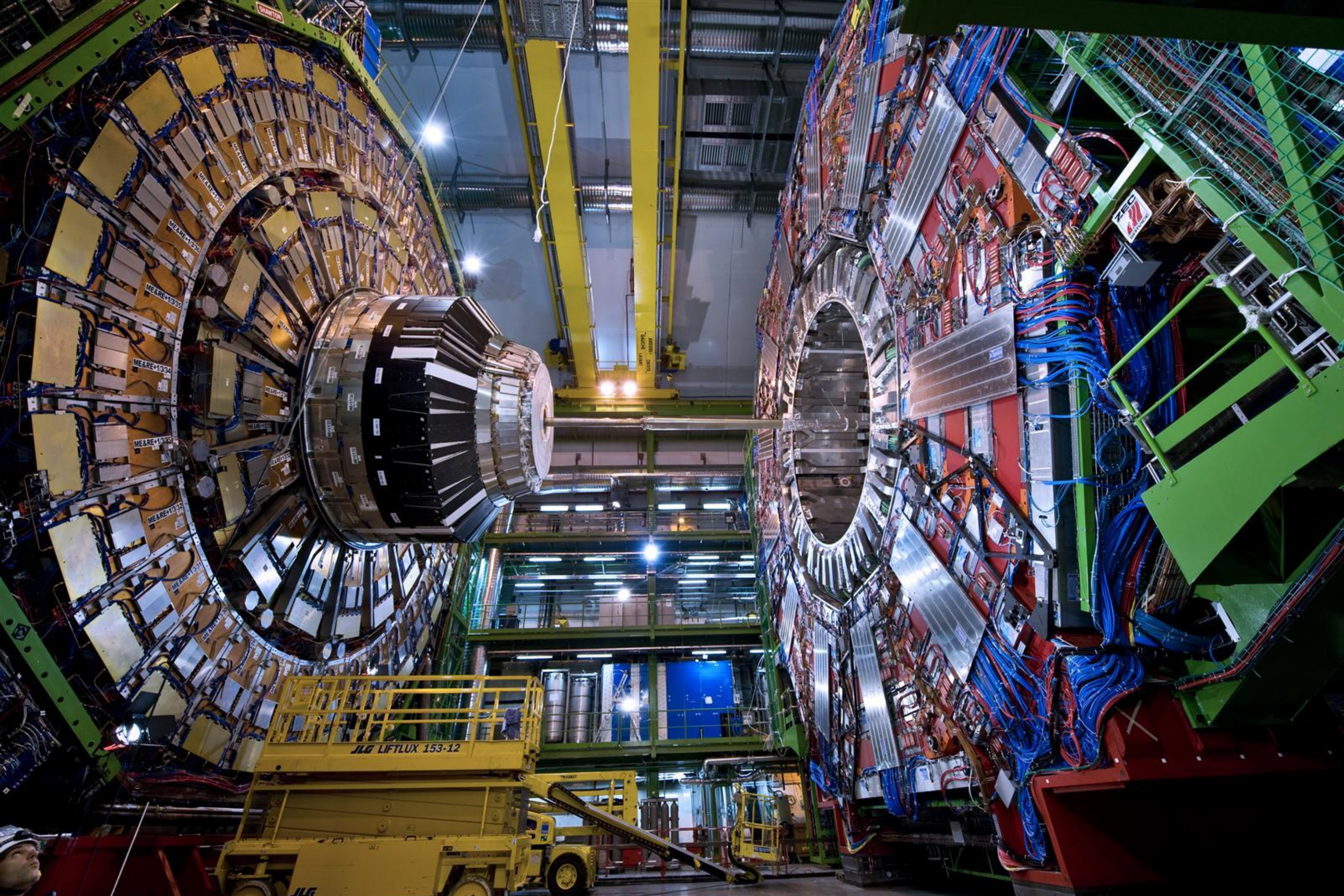
"Three quarks for Muster Mark!
Sure he has not got much of a bark
And sure any he has it's all beside the mark."
James Joyce, Finnegans Wake

Quantum Chromodynamics (QCD)

The Quark model of *hadrons*



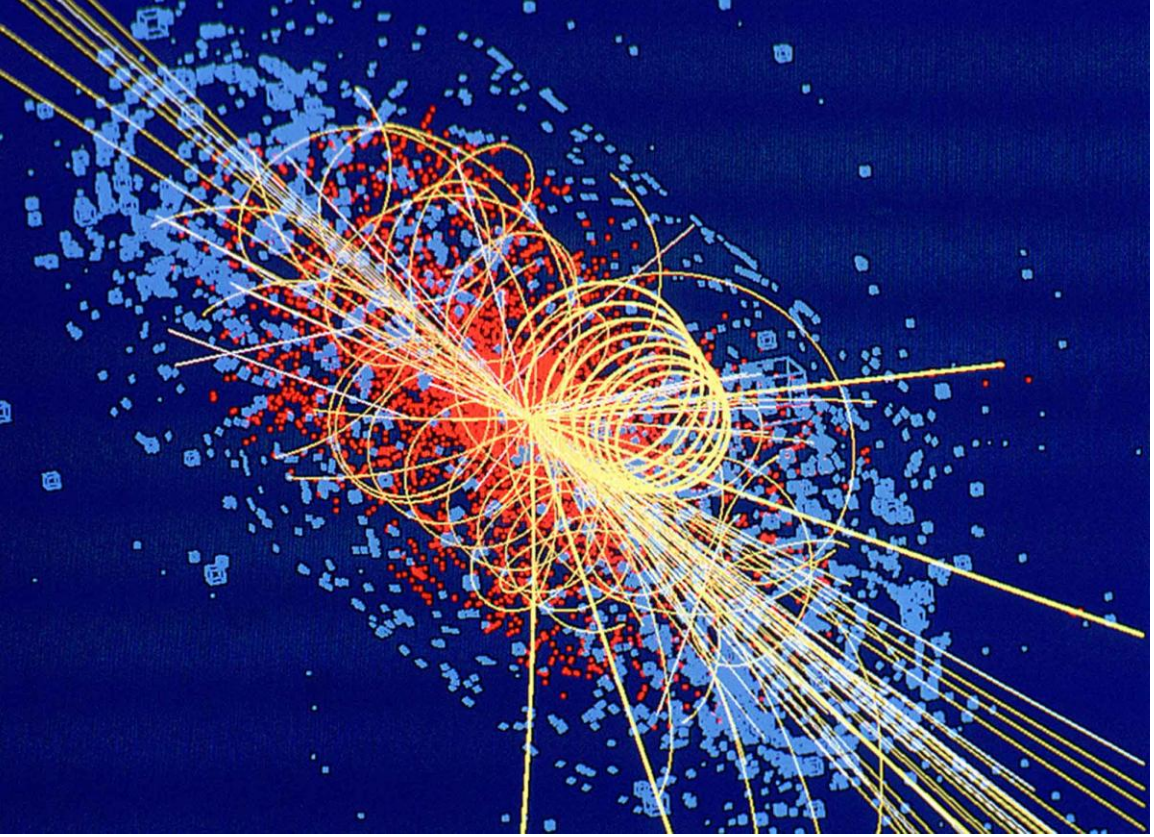
mass →
charge →
spin →
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
QUARKS
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
LEPTONS
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
GAUGE BOSONS



Higgs boson discovered at CERN in July 2012

All particles are within the **Higgs field**. Interactions with it confer *mass* to certain particles.

Peter Higgs
1929-



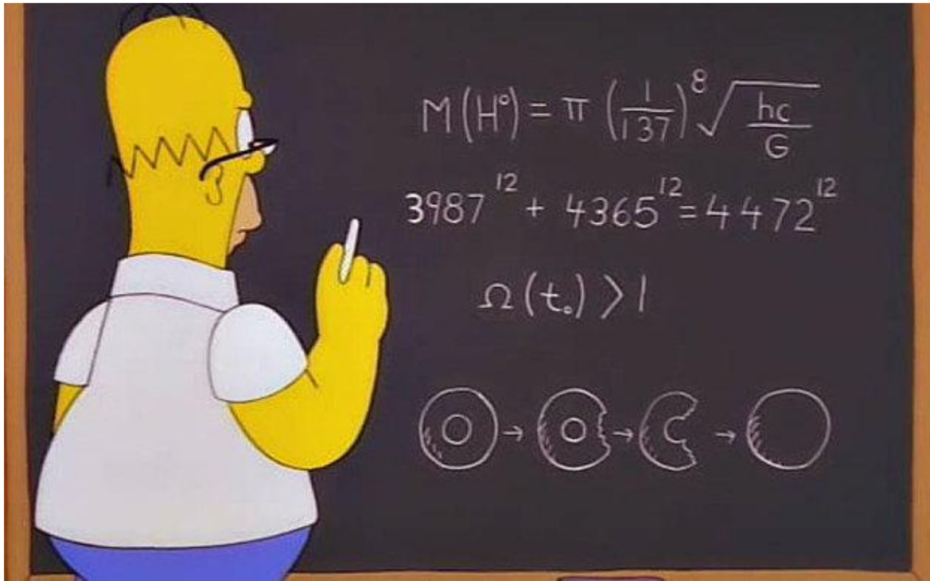
At CERN, particles (such as protons) are collided at very high energies. The high energies are achieved via acceleration using **electric fields**. Enormous* voltages are used!

Magnetic fields are used to steer the particle beams in the circular beamlines

* 10^{12} volts

When particles such as protons collide, a plethora of other particles (i.e. hadrons or leptons) are formed.

The trajectories of these particles can be used to infer the mass and charge of these particles



The Standard Model of Particle Physics

Fermions are particles with half-integer spin
They obey the **Pauli Exclusion Principle**

Matter

Leptons
Spin half

Lepton	Charge	Mass (MeV/c^2)	Mean life (s)
ν_e	0	$< 15\,eV/c^2$	stable
ν_μ	0	< 0.17	stable
ν_τ	0	< 18.2	stable
e	±1	0.511^a	stable
μ	±1	105.658^b	2.197×10^{-6c}
τ	±1	$1777.0(\pm3)$	$290.0(\pm12) \times 10^{-15}$

Quarks (spin 1/2)			
Name	Flavour	Mass (GeV/c^2)	Charge (e)
up	u	≈ 0.35	$+2/3$
down	d	$m_d \approx m_u$	$-1/3$
charm	c	1.5	$+2/3$
strange	s	0.5	$-1/3$
top	t	$174(\pm5)$	$+2/3$
bottom	b	4.5	$-1/3$

Hadrons (made from quarks)

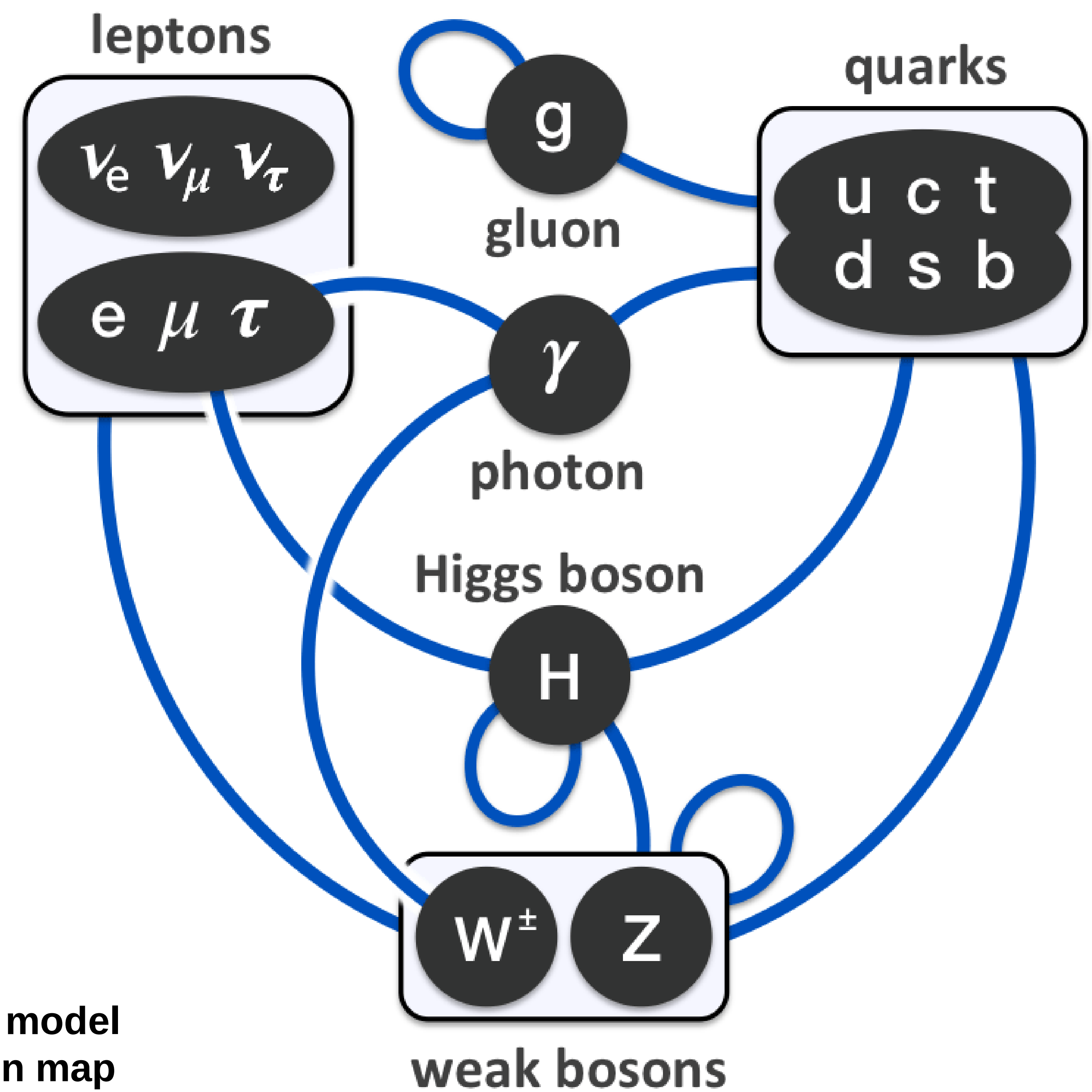
Baryons
(three quarks)
Half-integer spin

proton = uud
neutron = udd

Mesons (quark + anti-quark pair)
Integer spin

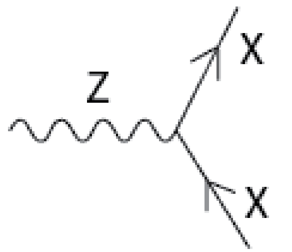
Mesons are also Bosons as they have integer spin. They *don't* have to obey the Pauli Exclusion Principle

Interactions between particles proceed via exchange of **Gauge Bosons**
e.g. photon, W^+, W^- , Z^o, gluon, graviton(?)

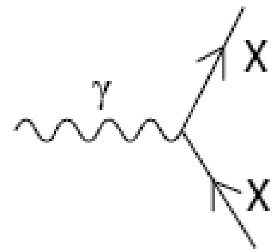


Standard model interaction map

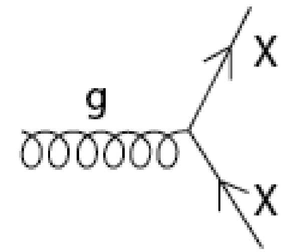
Standard Model Interactions
(Forces Mediated by Gauge Bosons)



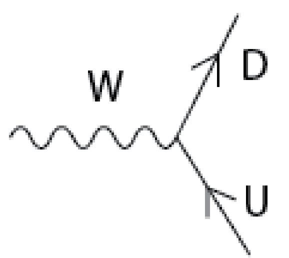
X is any fermion in the Standard Model.



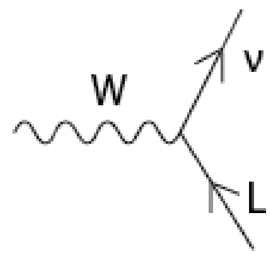
X is electrically charged.



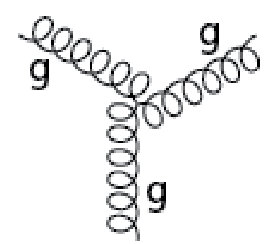
X is any quark.

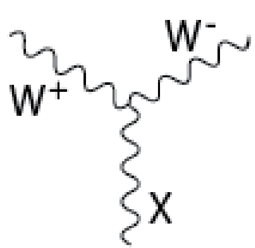


U is a up-type quark;
D is a down-type quark.

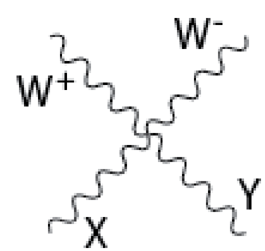


L is a lepton and ν is the corresponding neutrino.

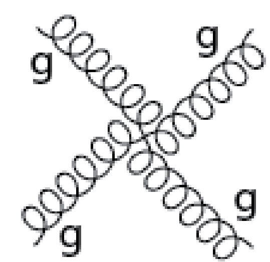




X is a photon or Z-boson.



X and Y are any two electroweak bosons such that charge is conserved.



Gauge Bosons ($J^P = 1^-$)						
Force	Gauge Boson	Charge (e)	Mass (GeV/c^2)	Full Width (GeV)	Decay Mode	Branching Ratio (%)
E-M	γ	$< 5 \times 10^{-30}$	$< 2 \times 10^{-16}\, eV/c^2$	stable		
Weak (Charged)	$W^{\pm}$	± 1	80.41(±10)	2.06(±6)	$e\nu_e$	10.9(±4)
					$\mu\nu_\mu$	10.2(±5)
					$\tau\nu_\tau$	11.3(±8)
					hadrons	67.8(±10)
Weak (Neutral)	Z^0	0	91.187(±7)	2.490(±7)	ee	3.366(±8)
					$\mu\mu$	3.367(±13)
					$\tau\tau$	3.360(±15)
					$\nu\nu$	20.01(±16)
					hadrons	69.90(±15)
Strong	g	0	0	stable		

Boson – integer spin

Fermion– half integer spin

Quarks (spin 1/2)

Name	Flavour	Mass (GeV/c^2)	Charge (e)
up	u	≈ 0.35	$+2/3$
down	d	$m_d \approx m_u$	$-1/3$
charm	c	1.5	$+2/3$
strange	s	0.5	$-1/3$
top	t	$174(\pm 5)$	$+2/3$
bottom	b	4.5	$-1/3$

Leptons (spin 1/2)					
Lepton	Charge	Mass (MeV/c^2)	Mean life (s)	Lepton Decay Mode	Branching Ratio (%)
ν_e	0	$< 15\,eV/c^2$	stable		
ν_μ	0	< 0.17	stable		
ν_τ	0	< 18.2	stable		
e	± 1	0.511^a	stable		
μ	± 1	105.658^b	2.197×10^{-6c}	$e^- \bar{\nu}_e \nu_\mu$	≈ 100
τ	± 1	$1777.0(\pm 3)$	$290.0(\pm 12) \times 10^{-15}$	$\mu^- \bar{\nu}_\mu \nu_\tau$	$17.37(\pm 9)$
				$e^- \bar{\nu}_e \nu_\tau$	$17.81(\pm 7)$
				hadrons $+\nu_\tau$	≈ 65

Fermion– half integer spin

Mesons
(quark + anti-quark pair)

Pseudoscalar Mesons ($J^P = 0^-$)

Particle	Quark Content	Mass (MeV/c²)	Mean Life (s) or Width (keV)	Decay Mode	Branching Ratio (%)
$\pi^\pm$	$u\bar{d}, d\bar{u}$	139.5700(±4)	$2.6033(\pm5) \times 10^{-8}$	$\mu^-\bar{\nu}_\mu$	≈ 100
π^0	$(u\bar{u} - d\bar{d})/\sqrt{2}$	134.9764(±6)	$8.4(\pm6) \times 10^{-17}$	$\gamma\gamma$	98.80(±3)
η	see note a	547.3(±1)	1.2(±1)	$\gamma\gamma$	39.2(±3)
				$\pi^0\pi^0\pi^0$	32.2(±4)
				$\pi^+\pi^-\pi^0$	23.1(±5)
				$\pi^+\pi^-\gamma$	4.8(±1)
η'	see note a	957.8(±1)	0.20(±2)	$\pi^+\pi^-\eta$	44(±2)
				$\rho^0\gamma$	30(±1)
				$\pi^0\pi^0\eta$	21(±1)
$K^\pm$	$u\bar{s}, s\bar{u}$	493.677(±16)	$1.239(\pm2) \times 10^{-8}$	$\mu^-\bar{\nu}_\mu$	63.5(±2)
				$\pi^-\pi^0$	21.2(±1)
				$\pi^+\pi^-\pi^-$	5.59(±5)
				$\pi^0\mu^-\bar{\nu}_\mu$	3.18(±8)
				$\pi^0 e^-\bar{\nu}_e$	4.82(±6)
$K^0, \overline{K^0}$	$d\bar{s}, s\bar{d}$	497.67(±3)	K^0_S $0.8934(\pm8) \times 10^{-10}$	$\pi^+\pi^-$	68.6(±3)
				$\pi^0\pi^0$	31.4(±3)
			K^0_L $5.17(\pm4) \times 10^{-8}$	$\pi^0\pi^0\pi^0$	21.1(±3)
				$\pi^+\pi^-\pi^0$	12.6(±2)
				$\pi^\pm\mu^\mp\nu_\mu$	27.2(±3)
				$\pi^\pm e^\mp\nu_e$	38.8(±3)
$D^\pm$	$c\bar{d}, d\bar{c}$	1869.3(±5)	$1.06(\pm2) \times 10^{-12}$	$e^- +$ any[b]	17(±2)
				$K^- +$ any	24(±3)
				$K^+ +$ any	6(±1)
				$K^0 +$ any	
				plus	
				$\overline{K^0} +$ any	59(±7)
$D^0, \overline{D^0}$	$u\bar{c}, c\bar{u}$	1864.6(±5)	$0.415(\pm4) \times 10^{-12}$	$K^- +$ any[c]	53(±4)
				$K^+ +$ any	3.4(±5)
				$e^+ +$ any	6.8(±3)
				$\mu^+ +$ any	6.6(±8)
				$\overline{K^0} +$ any	
				plus	
				$K^0 +$ any	42(±5)
$D_s^\pm$	$c\bar{s}, s\bar{c}$	1968.5(±6)	$0.47(\pm2) \times 10^{-12}$	seen	
$B^\pm$	$u\bar{b}, b\bar{u}$	5279(±2)	$1.65(\pm4) \times 10^{-12}$	seen	
$B^0, \overline{B^0}$	$d\bar{b}, b\bar{d}$	5279(±2)	$1.56(\pm4) \times 10^{-12}$	seen	
$B^0_s, \overline{B^0_s}$	$s\bar{b}, b\bar{s}$	5369(±2)	$1.54(\pm7) \times 10^{-12}$	seen	
η_c	$c\bar{c}$	2980(±2)	13(±4) MeV	hadrons	

[a] η and η' are linear combinations of the quark state $(u\bar{u} + d\bar{d})/\sqrt{2}$ and $s\bar{s}$.
[b] D^- decay modes; [c] D^0 decay modes.

Vector Mesons ($J^P = 1^-$)

Particle	Quark Content	Mass (MeV/c²)	Full Width (MeV)	Decay Mode	Branching Ratio (%)
$\rho^\pm$	$u\bar{d}, d\bar{u}$	770.0(±8)	151(±1)	$\pi\pi$	100
ρ^0	$(u\bar{u} - d\bar{d})/\sqrt{2}$				
ω	$(u\bar{u} + d\bar{d})/\sqrt{2}$	781.9(±1)	8.41(±9)	$\pi^+\pi^-\pi^0$	88.8(±7)
				$\pi^0\gamma$	8.5(±5)
				$\pi^+\pi^-$	2.2(±3)
ϕ	$s\bar{s}$	1019.413(±8)	4.43(±5)	K^+K^-	49.1(±8)
				$K^0_L K^0_S$	34.1(±6)
$K^{*\pm}$	$u\bar{s}, s\bar{u}$	891.7(±3)	50.8(±9)	$K\pi$	≈ 100
$K^{*0}, \overline{K^{*0}}$	$d\bar{s}, s\bar{d}$	896.1(±3)	50.5(±6)	$K\pi$	≈ 100
$D^{*\pm}$	$c\bar{d}, d\bar{c}$	2010.0(±5)	< 0.13	$D^0\pi^-$[a]	68(±1)
				$D^-\pi^0$	31(±3)
$D^{*0}, \overline{D^{*0}}$	$u\bar{c}, c\bar{u}$	2006.7(±5)	< 2.1	$D^0\pi^0$[b]	62(±3)
				$D^0\gamma$	38(±3)
$D_s^{*\pm}$	$c\bar{s}, s\bar{c}$	2112.4(±7)	< 1.9	seen	
B^*	$u\bar{b}, b\bar{u}, d\bar{b}, b\bar{d}, s\bar{b}, b\bar{s}$	5325(±2)		$B\gamma$ seen	
J/ψ	$c\bar{c}$	3096.88(±4)	87(±5) keV	hadrons	87.7(±5)
				e^+e^-	6.0(±2)
				$\mu^+\mu^-$	6.0(±2)
$\Upsilon(1s)$	$b\bar{b}$	9460.4(±2)	53(±2) keV	$\tau^+\tau^-$	2.7(±2)
				e^+e^-	2.5(±2)
				$\mu^+\mu^-$	2.48(±7)

[a] D^{*-} decay modes; [b] D^{*0} decay modes.

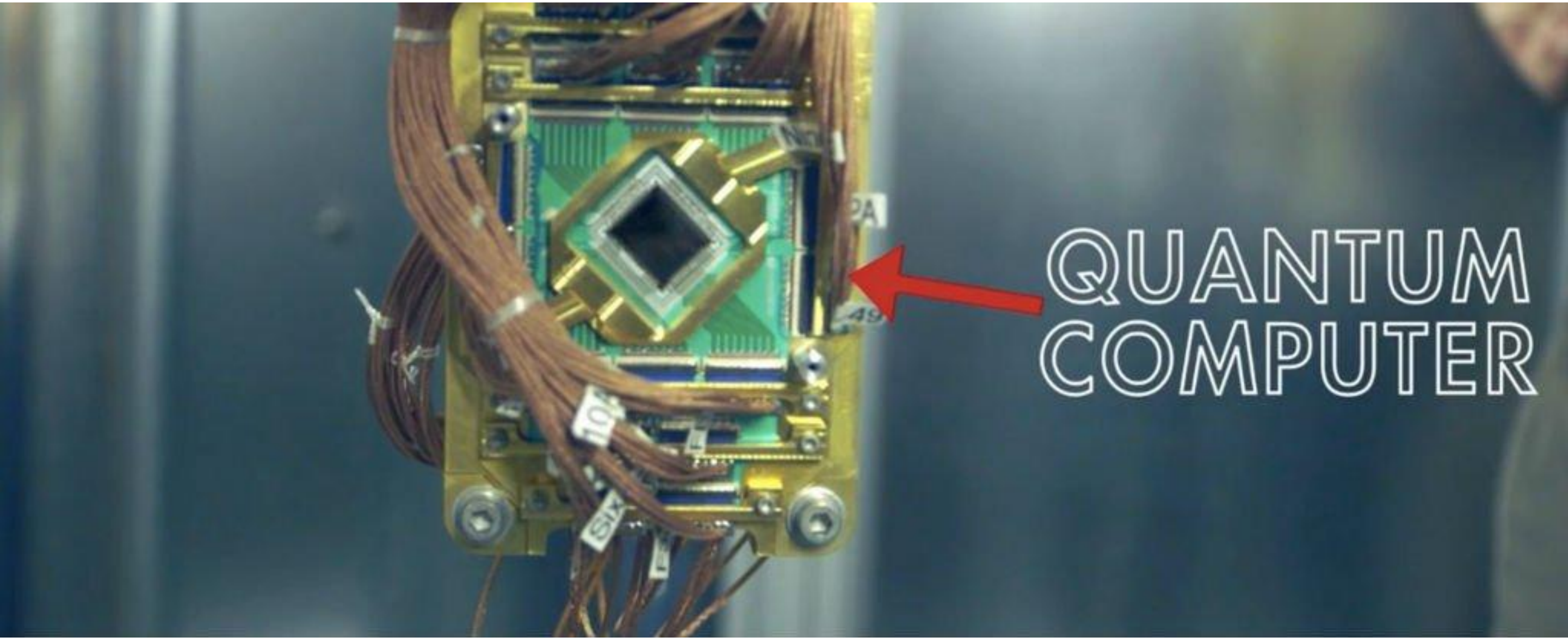
Boson - integer spin

Baryons ($J^P = 1/2^+$)					
Particle	Quark Content	Mass (MeV/c^2)	Mean Life (s) or Full Width (MeV)	Decay Mode	Branching Ratio (%)
p	uud	938.2723($\pm$3)	$> 1.6 \times 10^{25}$ years		
n	udd	939.5656($\pm$3)	887($\pm$2)	$pe^- \bar{\nu}_e$	100
Λ^0	uds	1115.683($\pm$6)	$2.63(\pm 2) \times 10^{-10}$	$p\pi^-$	63.9($\pm$5)
				$n\pi^0$	35.8($\pm$5)
Σ^+	uus	1189.37($\pm$7)	$0.799(\pm 4) \times 10^{-10}$	$p\pi^0$	51.6($\pm$3)
				$n\pi^+$	48.3($\pm$3)
Σ^0	uds	1192.64($\pm$2)	$7.4(\pm 7) \times 10^{-20}$	$\Lambda^0\gamma$	100
Σ^-	dds	1197.45($\pm$3)	$1.48(\pm 1) \times 10^{-10}$	$n\pi^-$	99.848($\pm$5)
Ξ^0	uss	1314.9($\pm$6)	$2.90(\pm 9) \times 10^{-10}$	$\Lambda^0\pi^0$	99.54($\pm$5)
Ξ^-	dss	1321.3($\pm$1)	$1.64(\pm 2) \times 10^{-10}$	$\Lambda^0\pi^-$	99.89($\pm$4)
Λ_c^+	udc	2284.9($\pm$6)	$2.1(\pm 1) \times 10^{-13}$	seen	
Λ_b	udb	5624($\pm$9)	$1.14(\pm 8) \times 10^{-12}$	seen	
Baryons ($J^P = 3/2^+$)					
Δ	uuu, uud udd, ddd	≈ 1232	≈ 120	$N\pi$	> 99
Σ^*	uus, uds, dds	≈ 1385	≈ 36	$\Lambda^0\pi$	88($\pm$2)
				$\Sigma\pi$	12($\pm$2)
Ξ^*	uss, dss	≈ 1530	≈ 9	$\Xi\pi$	100
Ω^-	sss	1672.5($\pm$3)	$0.82(\pm 1) \times 10^{-10}$	$\Lambda^0 K^-$	67.8($\pm$7)
				$\Xi^0\pi^-$	23.6($\pm$7)
				$\Xi^-\pi^0$	8.6($\pm$4)

Baryons
(Three quarks)

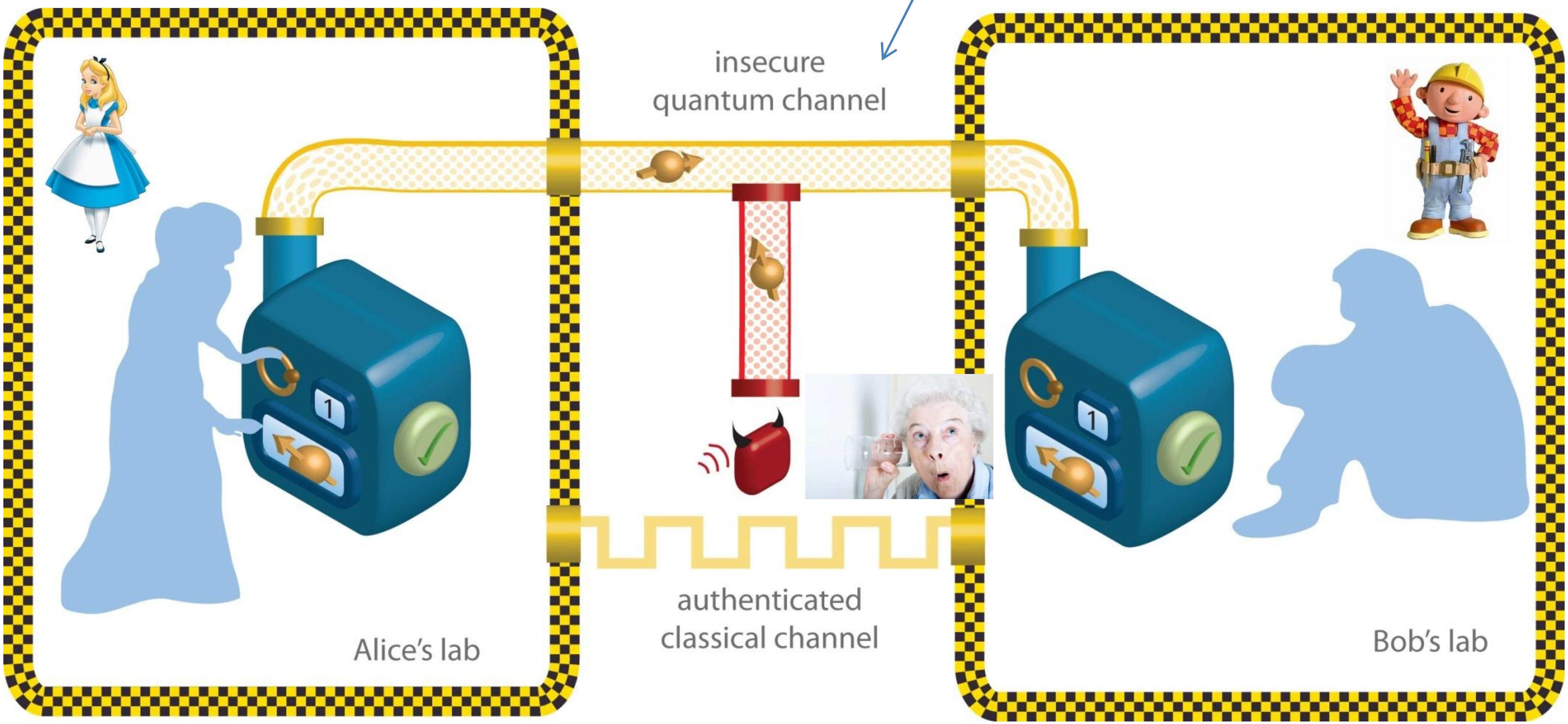
**Fermion–
half integer
spin**

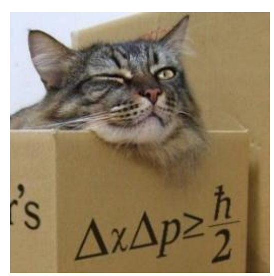
A QUANTUM FUTURE…


QUANTUM
COMPUTER

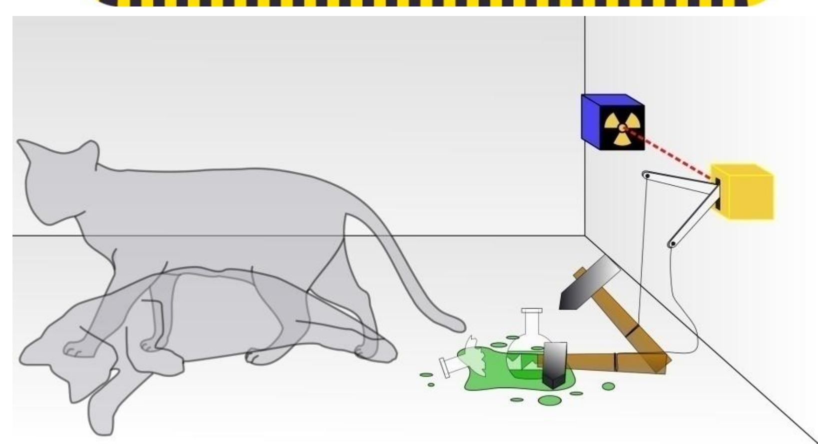
The Quantum future of cryptography

Here you can tell whether Eve has been listening!





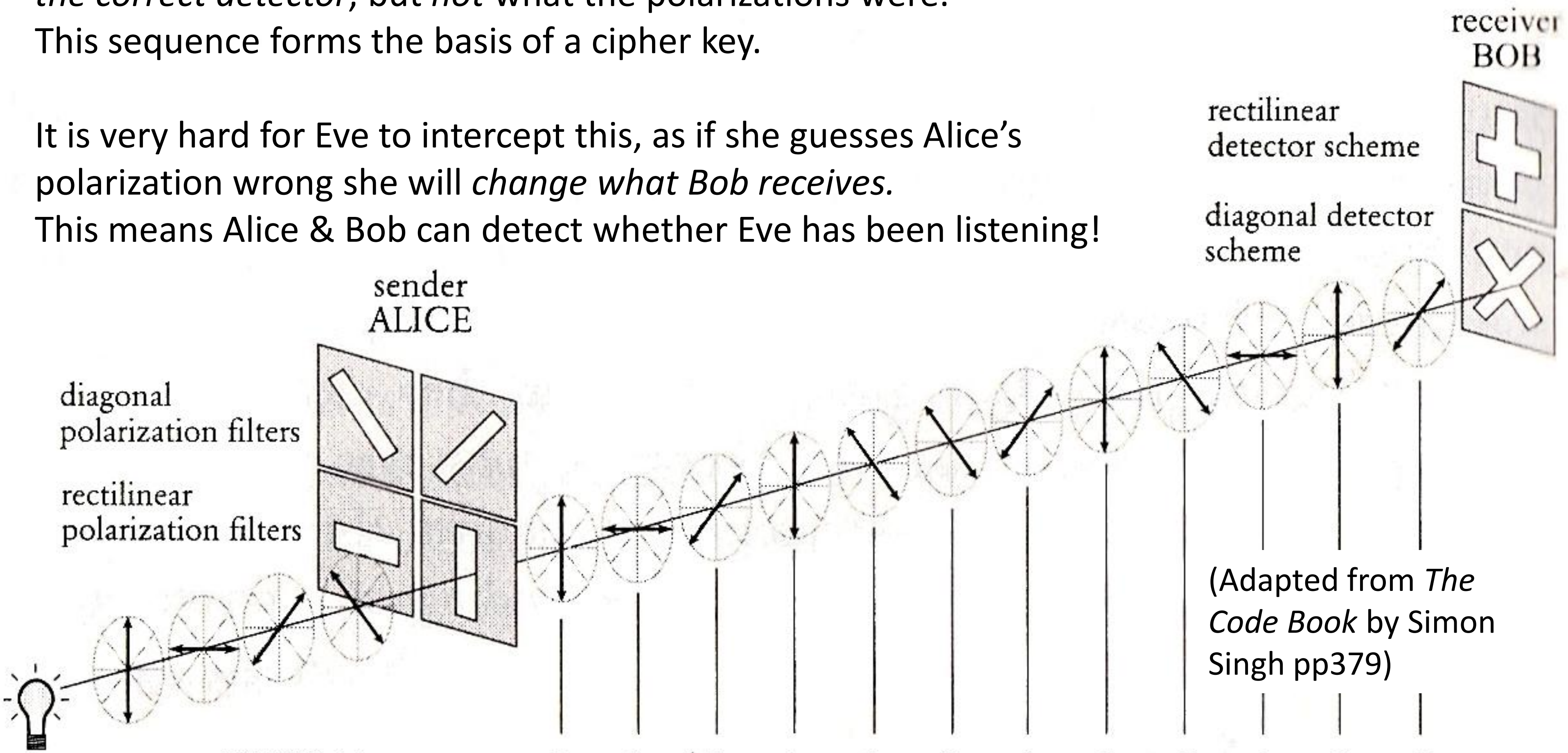
Erwin
Schrödinger
(1887-1961)



If you intercept a photon, you will force its polarization to be that of the detector.
In Quantum Mechanics your *act of measurement collapses the wavefunction.*

Alice sends Bob a message based upon photons of different polarizations.
Alice & Bob communicate to agree *which photons were intercepted with the correct detector*, but *not* what the polarizations were.
This sequence forms the basis of a cipher key.

It is very hard for Eve to intercept this, as if she guesses Alice's polarization wrong she will *change what Bob receives.*
This means Alice & Bob can detect whether Eve has been listening!



(Adapted from *The Code Book* by Simon Singh pp379)

ALICE's bit sequence	1	0	1	1	0	0	1	1	0	0	1	1
BOB's detection scheme	+	×	+	+	×	×	+	+	×	+	×	×
BOB's measurements	1	0	0	1	0	0	1	1	0	0	0	1
Retained bit sequence	1	–	–	1	0	0	–	1	0	0	–	1

Further reading