Physics 3204

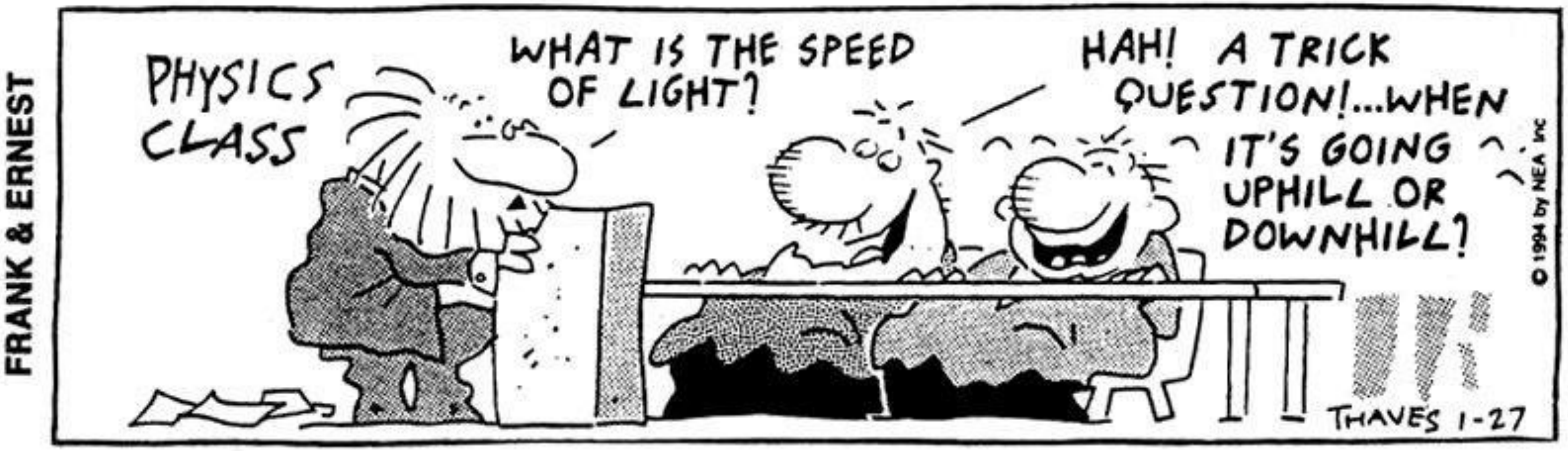
UNIT 3: Section 1

INTRODUCTION TO QUANTUM PHYSICS

Text Reference:
17.1-17.3

Proceed with caution

- Quantum Physics can be the most difficult (conceptually) in the course. Do not get discouraged. It all makes sense once you get through it.


FRANK & ERNEST
PHYSICS CLASS
WHAT IS THE SPEED OF LIGHT?
HAH! A TRICK QUESTION!...WHEN IT'S GOING UPHILL OR DOWNHILL?
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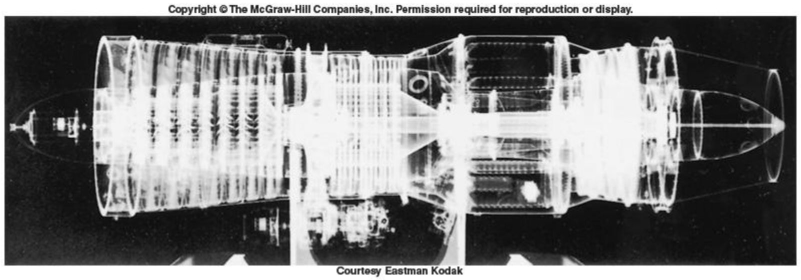
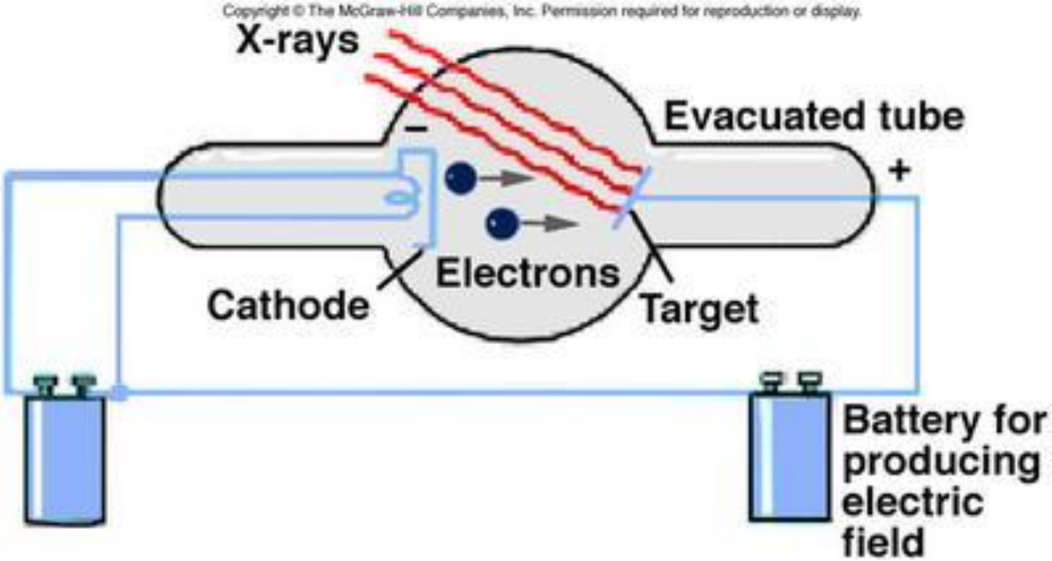
THAVES 1-27

X-rays



Wilhelm Roentgen accidentally discovered x-rays in 1895. In 1912, Max von Laue showed that x-rays are extremely high frequency EM waves. X-rays are produced by high energy electrons that are stopped suddenly; the electron KE is transformed into photon energy.

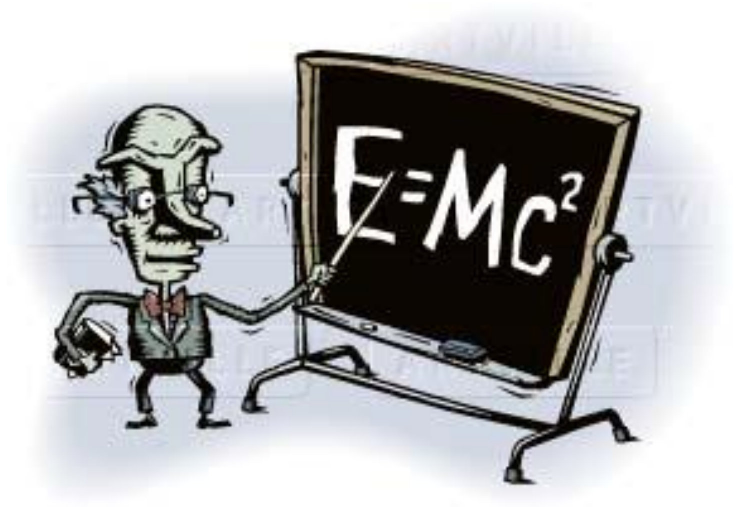
Wilhelm Roentgen
(1845-1923)



Radiation is the emission of energy as electromagnetic (EM) waves that comes from a source and travels through space and may be able to penetrate various materials.

Radiation is light that can transfer heat.

So far, our study of Physics has kept the ideas of **MATTER** and **ENERGY** as separate topics.



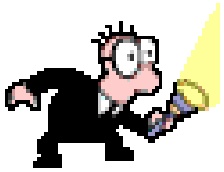
- We have learned that neither MATTER nor ENERGY can be created or destroyed

- We have also learned that they are very different phenomena

However, we need to consider what happens when ENERGY and MATTER interact and if whether or not they are indistinguishable

QUANTUM THEORY is the study of how MATTER and Energy are interrelated.

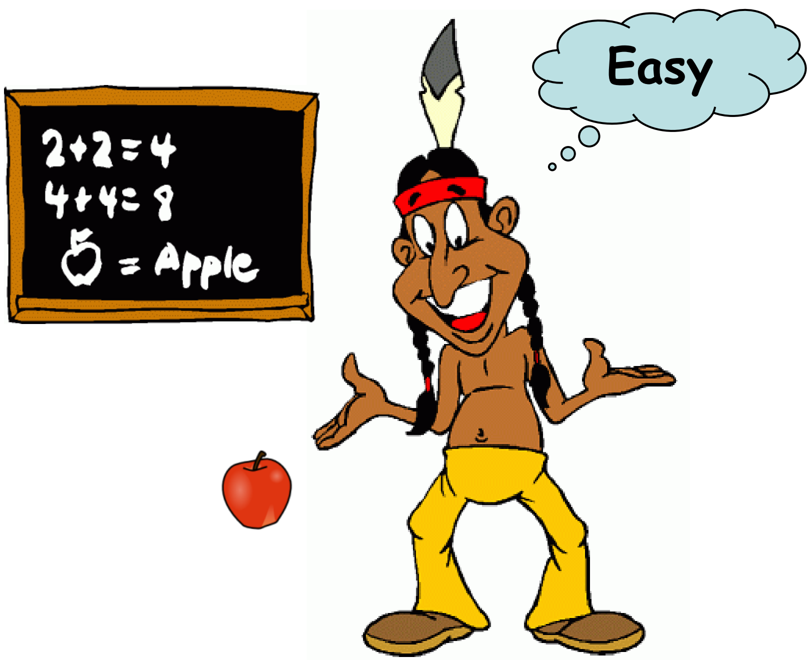
The energy we are referring to is LIGHT ENERGY

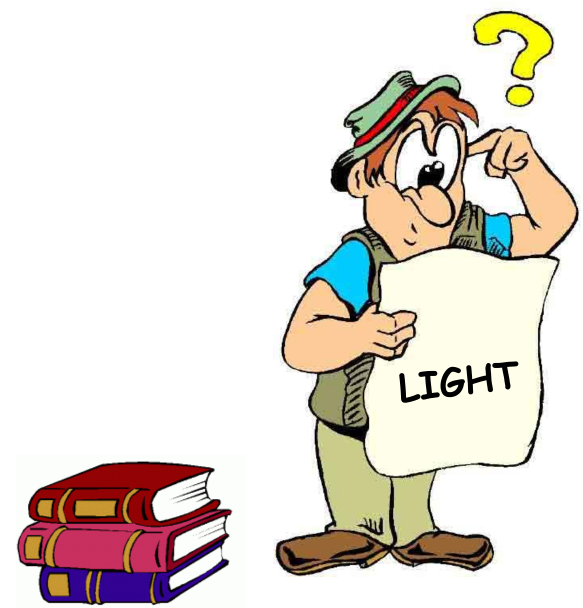


What is Light?

It's the late 1800's… and Everyone's Confused!

There was no problem in dealing with energy of large objects, such as apples falling, water waves crashing, and trains speeding along. But when it came to dealing with light energy and energy at the atomic and subatomic levels, all was not well.

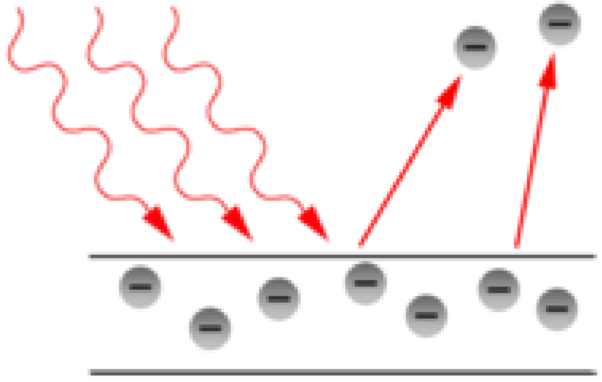




Problems with the Classical or Wave Theory of Light

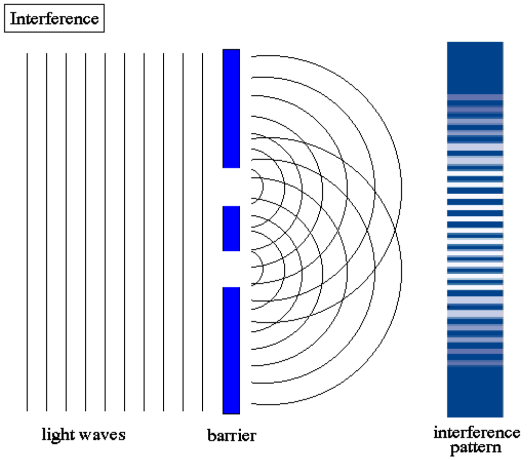
1. In some experiments, light exhibits particulate properties, such as momentum, a phenomenon that can't be explained in terms of the wave theory of light alone because a wave doesn't have mass

But then, it was discovered that when light hit certain materials, electrons were bounced out (something like a cue ball hitting a bunch of pool balls). In this situation, light seemed to be acting as tiny balls or particles.



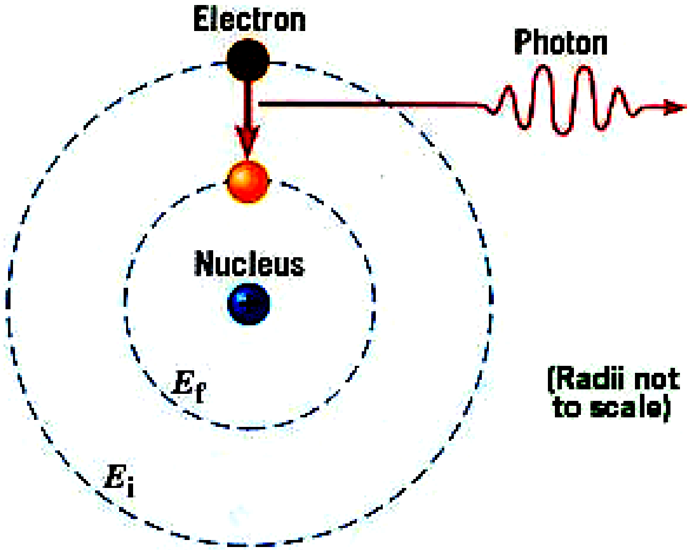
2. atomic particles exhibit wave properties

Electrons, protons, and neutrons are particles and therefore should not exhibit wave characteristics. Yet, diffraction of all three types of particles was observed in laboratory experiments



3. Neutral atoms are stable

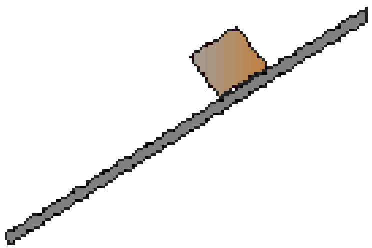
The view was that light is emitted because electrons lose energy and fall back to lower orbits around the nucleus. That is, the lost energy comes out as light. This was bothersome because it seemed that electrons should therefore finally spiral into the nucleus. Everyone knew that this was not happening, but there was no theory to explain what was going on in the atom as light was emitted.



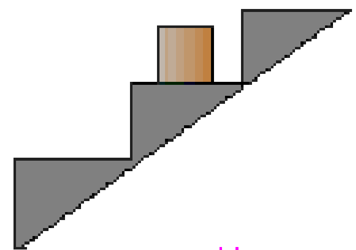
4. Energy is quantified

Finally in In 1900 Max Planck and Albert Einstein said that maybe we were looking at energy the wrong way where atomic matters are concerned. So they proposed the following model:

A new way to "see" light



representing
the classical
idea of energy



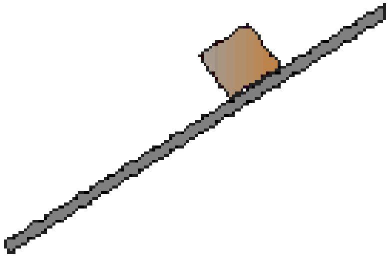
representing
the quantum
idea of energy

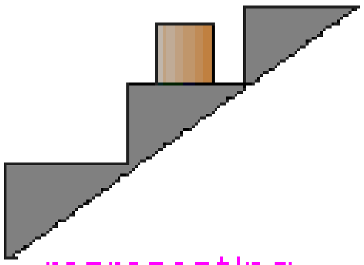
In this analogy the box represents an electron orbiting the nucleus.

- On the ramp, the box can have any amount of potential energy because it is everywhere on the ramp as it slides down.

- On the steps, the box can have only 4 specific amounts of energy

Classic vs. Quantum



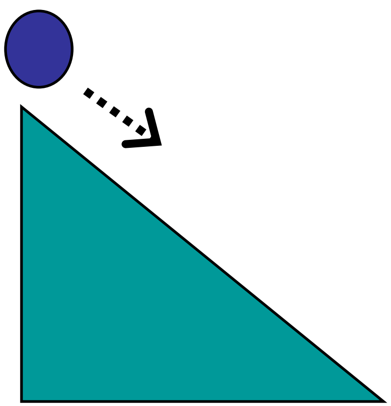


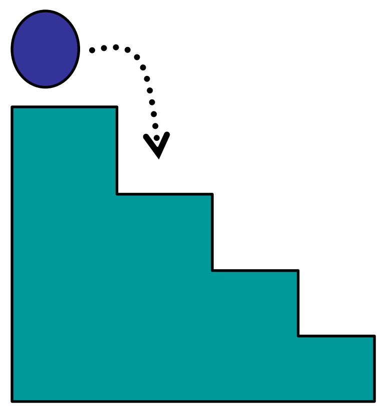
As the **electron** "falls from one step to the another", a fixed or discrete amount of energy is lost (that is, emitted as light). Planck named these discrete amounts **quanta**.

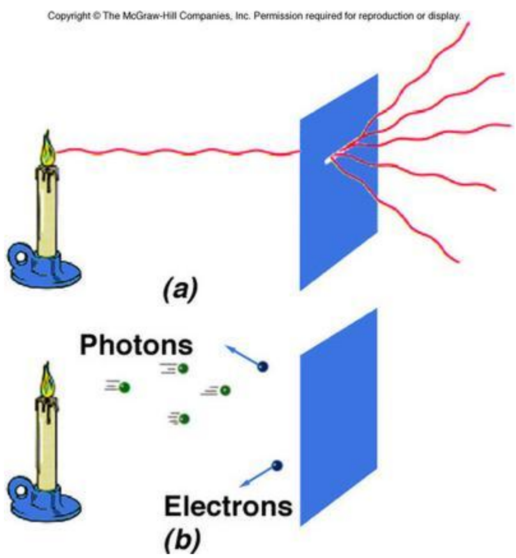
The idea of quanta satisfies very well the idea that sometimes the behavior of light is more like traveling particles than traveling waves. Each quantum of energy that is emitted can be viewed as a tiny packet or particle of light. The scientific name for each tiny packet is **photon**.

Wave – Particle Duality Theory of Light

Light exhibits either wave characteristics or particle (photon) characteristics, but never both at the same time. The wave theory of light and the quantum theory of light are both needed to explain the nature of light and therefore complement each other.



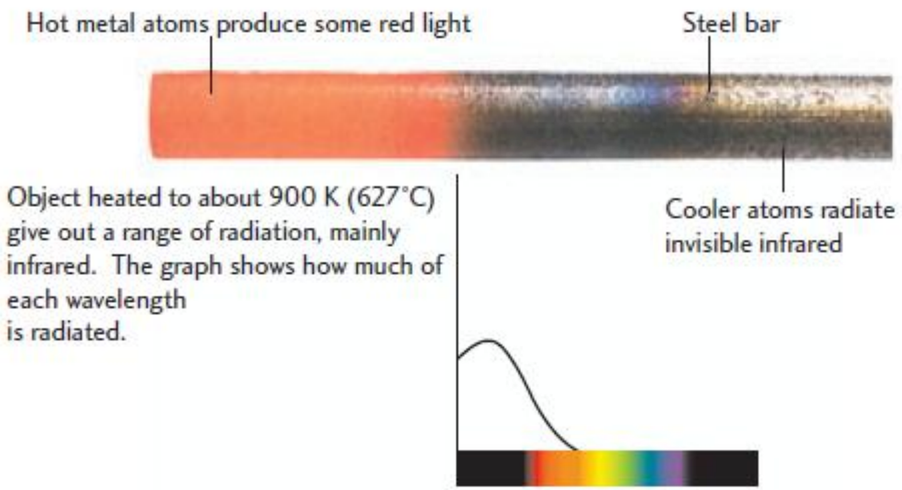


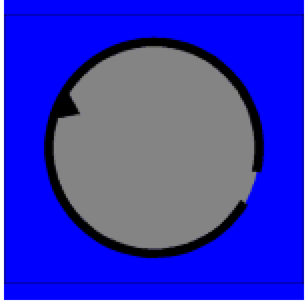


What is blackbody radiation?

All opaque objects above absolute zero Kelvin emit photons from a broad range of electromagnetic radiation called blackbody radiation. We feel this as heat.

Normally we cannot see this radiation unless a significant portion of the wavelengths lie in the visible part of the spectrum.

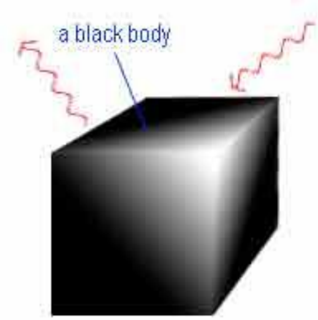




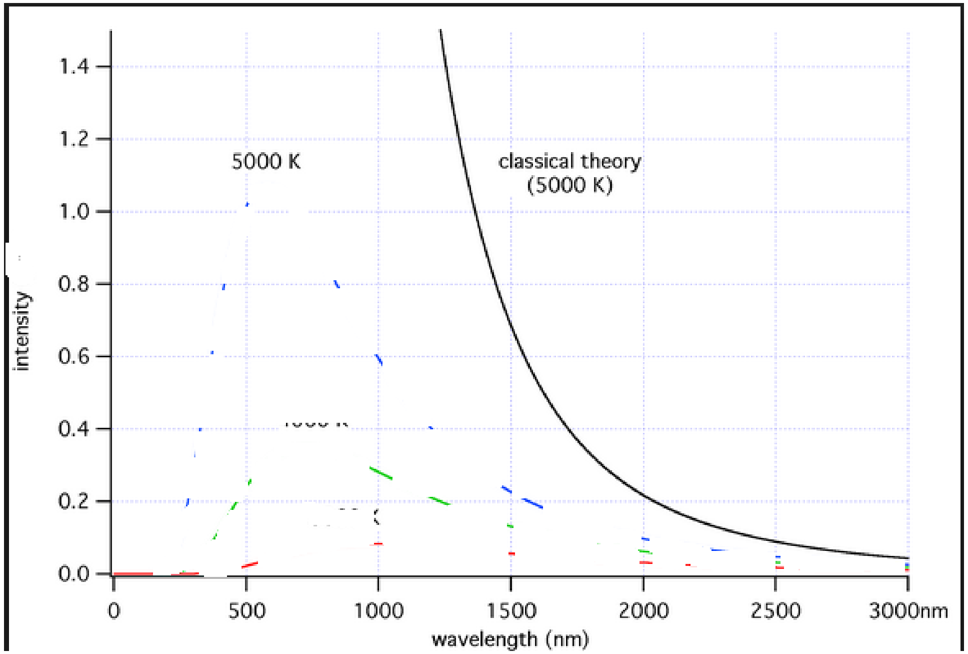
What is a blackbody?

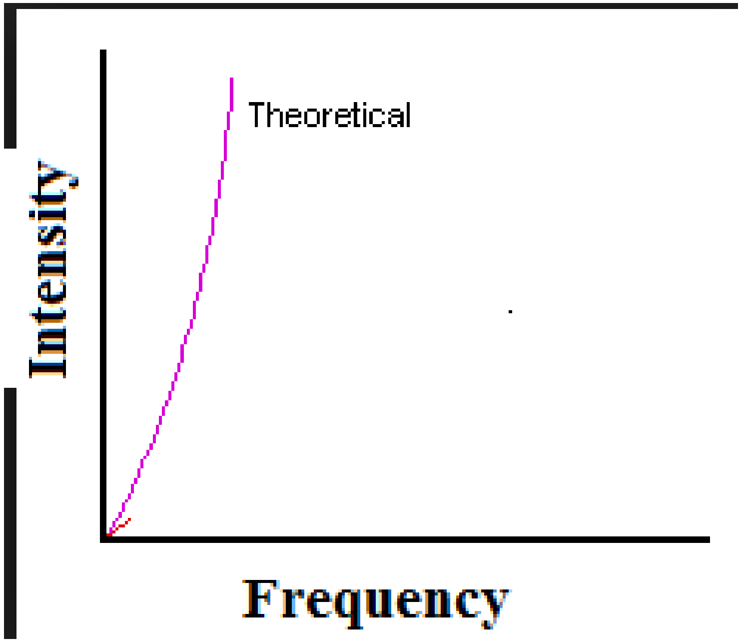
A **blackbody** is an ideal concept. It is that perfect object which absorbs all radiation that falls on it. Such a body is obviously "black" in the usual sense because it absorbs all light that falls on it. However, it also absorbs all other types of electromagnetic radiation that happens to strike it.

A very interesting outcome from experiments is the fact that objects which are excellent absorbers are also excellent emitters. So, a blackbody (or an object that is very nearly like an ideal blackbody) will emit radiation more efficiently than any other object. This radiation is called **blackbody radiation**



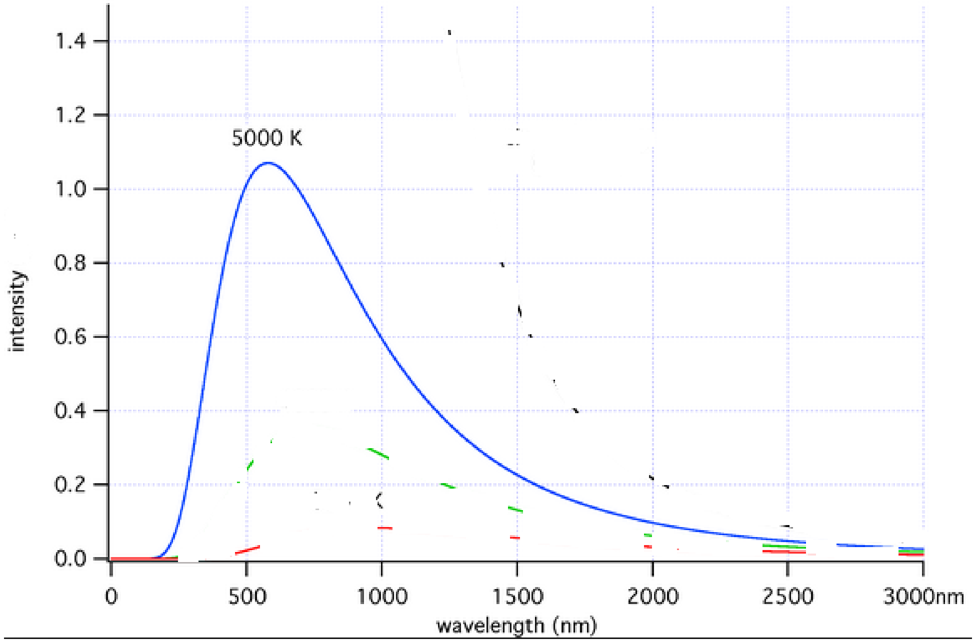
Wave theory predicted that the energy given off by a black body would show a curve like this:

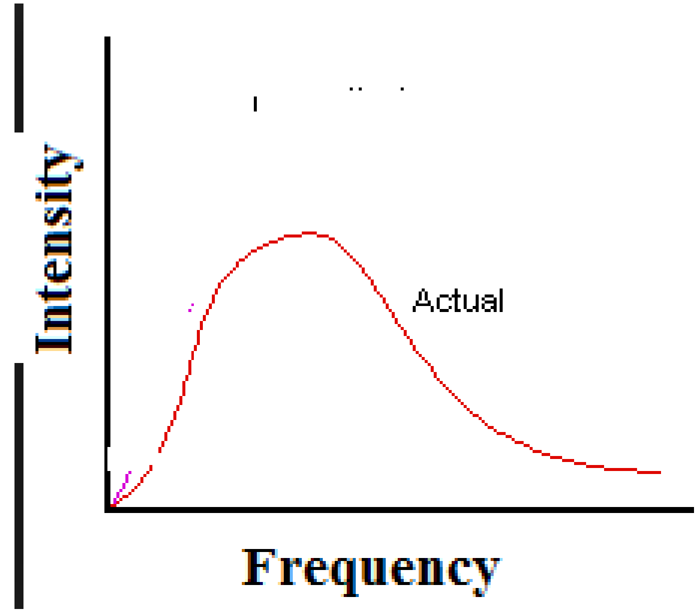




This means that as the wavelength decreased/frequency increased (UV light for example) the energy approaches infinity. This was not observed to happen

What they actually observed was

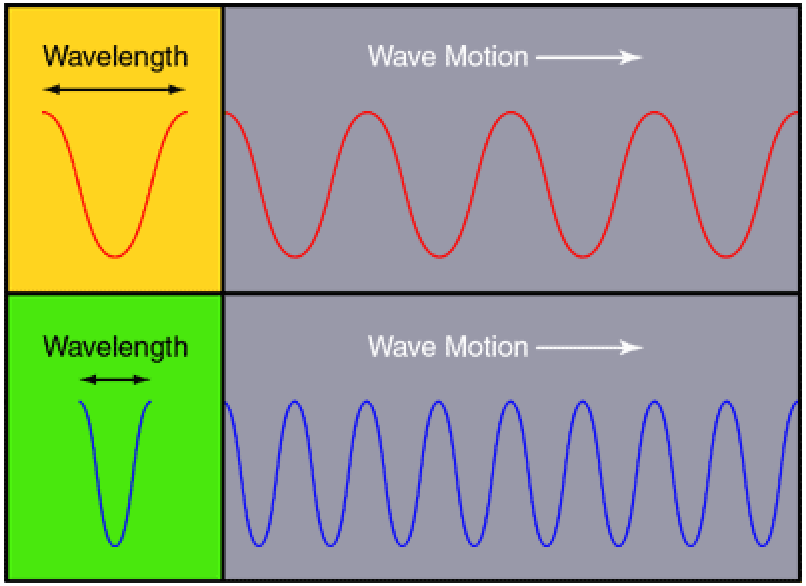




This discovery and its inconsistency with the wave theory of light was called the **UV catastrophe.** ***So we have here another example of a theory (waves) failing to account for the observed results...so it's time to change the theory.***

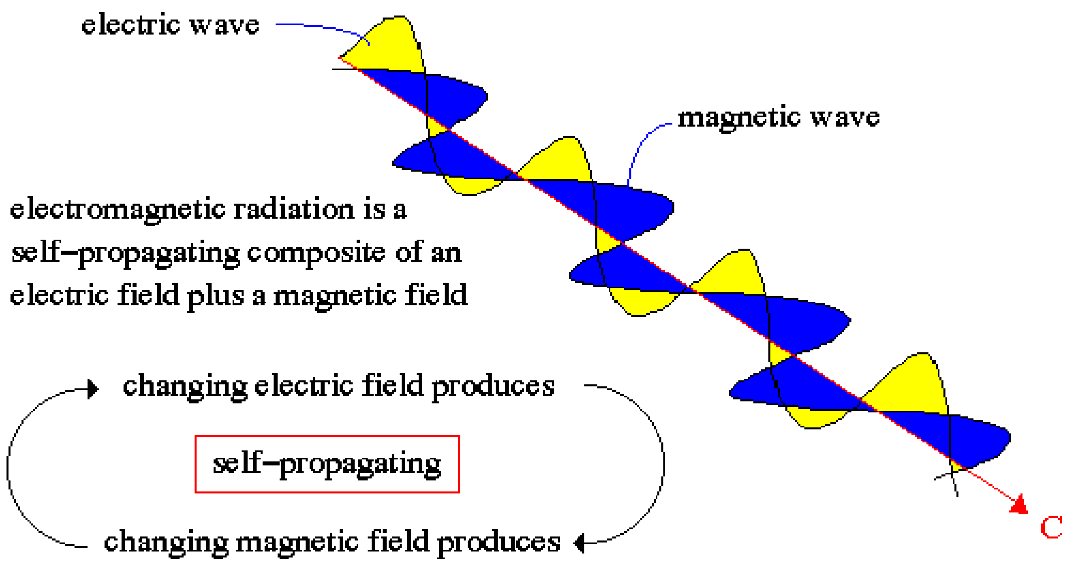
In 1900, Planck was able to make the observations agree with his theory which was the start of... quantum physic

When Max Planck hypothesized that electrons emit energy in certain discrete amounts, he had to abandoned the idea that the amount of energy depends on the **amplitude** of the wave (as in water waves), and instead went with the revolutionary idea that the energy depends on the **frequency** of the wave!



Planck stated that the emitted energy of one photon of light is directly proportional to the frequency associated with the wavelength of that light **(E α f).** In that one sentence Planck "married" the particle and wave nature of electromagnetic radiation.

There is no longer a need to say light has a particle nature only, or light has a wave nature only. We can now say light has a dual nature: **wave-particle.**



PLANK'S ENERGY FORMULA

A mathematical expression for a photon of energy

$$E = h\,f$$

Max Planck
(1858-1947)

Energy (E) is measured in Joules (J)

Plank's Constant (h) is $h = 6.63 \times 10^{-34}$ J· s.

Frequency (f) is measured in Hertz (s^{-1} or Hz)

Sometimes the Greek letter gamma (γ) is used to represent one photon of energy:

$$E_{\gamma} = h\,f$$

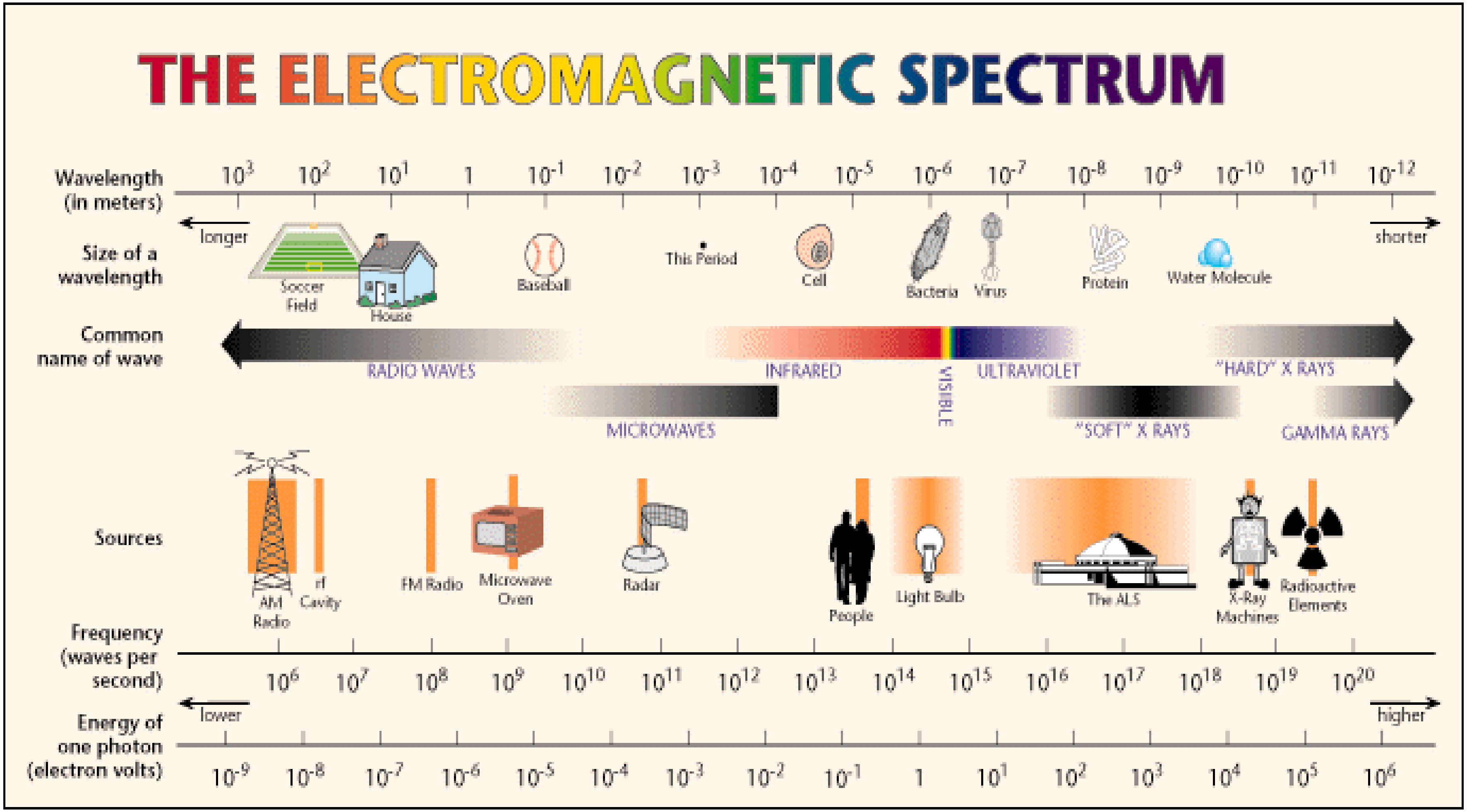
Planck also proposed that photons with very high frequencies carried more energy than ones with lower frequencies.

Recall the Ideal wave equation from Physics 2204: $\boldsymbol{v = f\,\lambda}$

Solving for f and using “c” for the speed of light, $\mathbf{f = c/\lambda}$

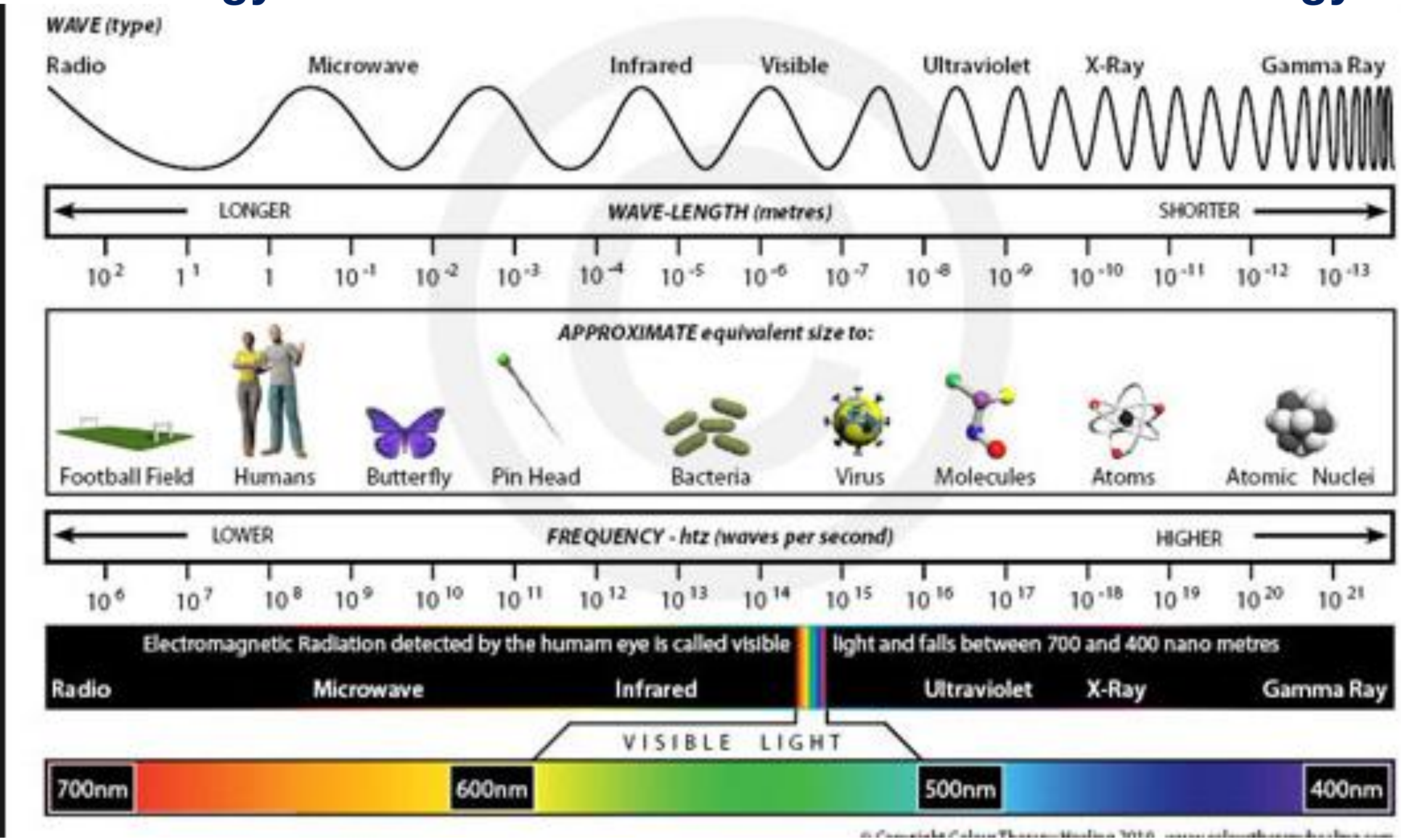
Substituting this in the equation $E_\gamma = hf$ becomes

$$\mathbf{E_\gamma = h\,(c/\lambda)}$$



The **electromagnetic spectrum** is the range of all possible electromagnetic radiation. Note: All electromagnetic radiation moves at the speed of light **(c = 3.0 x 10^{8} m/s)**

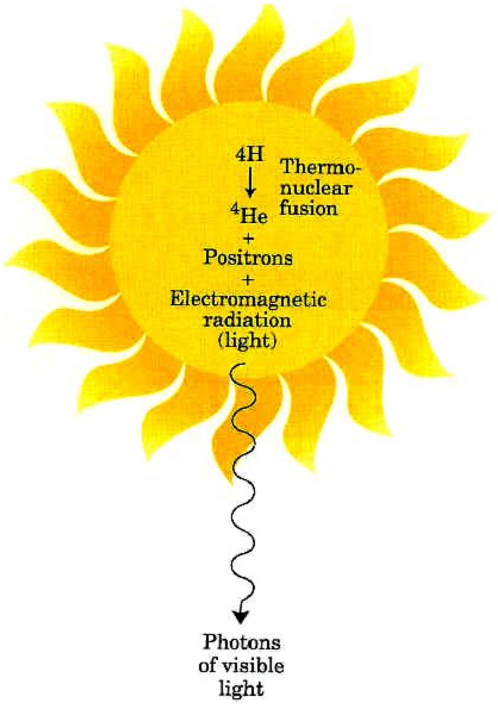
Low Energy ← → **High Energy**



Electromagnetic energy at a particular wavelength λ has an associated frequency *f* and photon energy *E*.

Practice exercise 1

Calculate the energy of a photon of blue light, $\lambda = 450$ nm.



Givens and unknown

$h = 6.63 \times 10^{-34}$ J ·s

$c = 3.00 \times 10^{8}$ m /s

$\lambda = 450 \text{ nm} = 450 \times 10^{-9} \text{ m} = 4.5 \times 10^{-7} \text{ m}$

$E\gamma = ?$

$$E_\gamma = \frac{hc}{\lambda}$$

$$E_\gamma = \frac{6.63 \times 10^{-34} \text{ J·s} \times 3.00 \times 10^{8} \text{ m/s}}{4.5 \times 10^{-7} \text{ m}}$$

$$E_\gamma = 4.4 \times 10^{-19} \text{ J}$$

Don't forget:

1 electron-volt or 1eV is an amount of energy equal to 1.6×10^{-19} J.

This allows us to change $E\gamma = 4.4 \times 10^{-19}$ J into 2.8 e V.

(To get 2.8 e V, just divide 4.4×10^{-19} J by 1.6×10^{-19} J.

Practice Exercise 2

What is the energy of a single photon of electromagnetic radiation from an FM station that is broadcasting at 99.1 MHz on your radio dial?

Givens and unknown

$h = 6.63 \times 10^{-34}$ J ·s

$c = 3.00 \times 10^{8}$ m /s

$f = 99.1$ MHz $= 99.1 \times 10^{6}$ cycles/s written as 9.91×10^{7} cycles /s

$$E_\gamma = hf$$

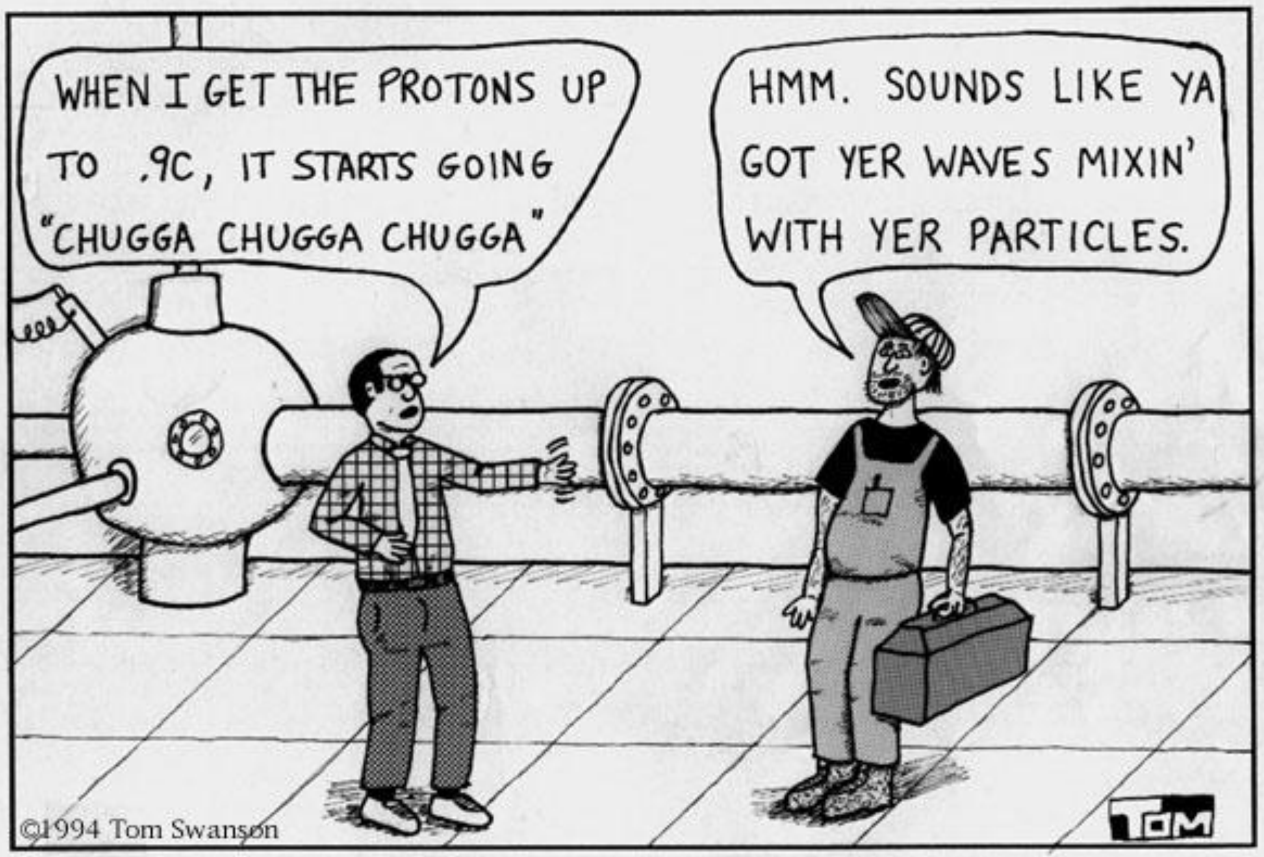
$$E_\gamma = 6.63 \times 10^{-34} \text{ J·s} \times 9.91 \times 10^{7} \text{ /s}$$

$$E_\gamma = 6.57 \times 10^{-26} \text{ J}$$

Or in eV:

$$E_\gamma = \frac{6.57 \times 10^{-26} \text{ J}}{1.6 \times 10^{-19} \text{ J/eV}} = 3.5 \times 10^{-7} \text{ eV}$$


If you ask me, the speed of light will never change. It just won't...
Planck's Constant Nagging



QUANTUM MECHANIC

Worksheet: Introduction to Quantum

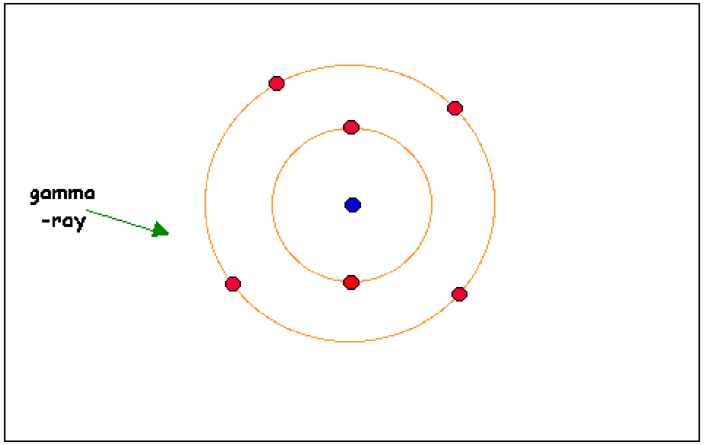
Video: What is light (3 min)

Magnetic Spectrum Magnetic Spectrum (3 min) [OPTIONAL]

Physics 3204

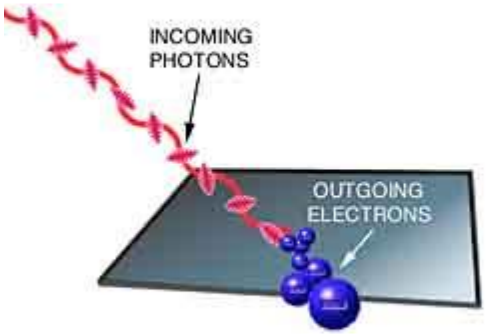
UNIT 3: Section 2

The Photoelectric Effect



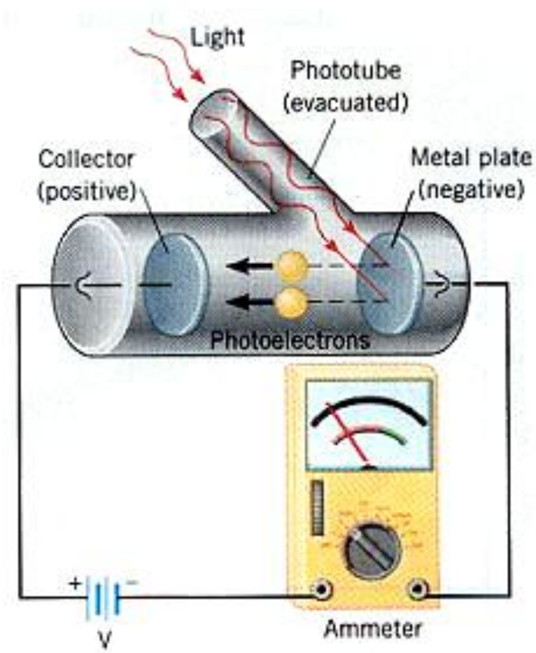
Text reference:
17.3

What's Happening?



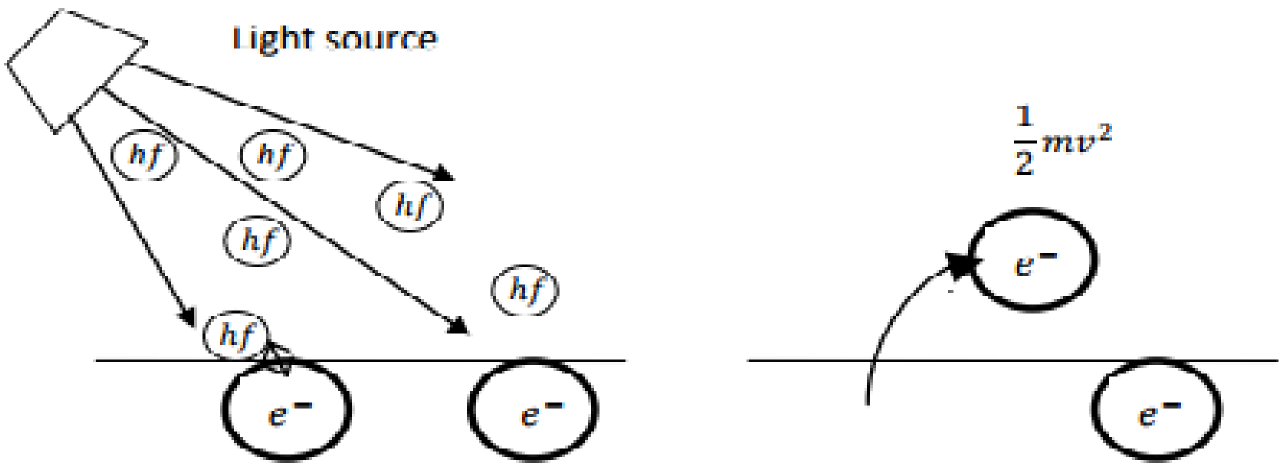
Photoelectric Effect refers to the emission, or ejection, of electrons from the surface of, generally, a metal in response to incident light.

The figure right may be seen on p. 702 of your textbook. Notice that as light hits the negative plate electrons are bounced out of the plate. This is called the **photoelectric effect.**



A few points:

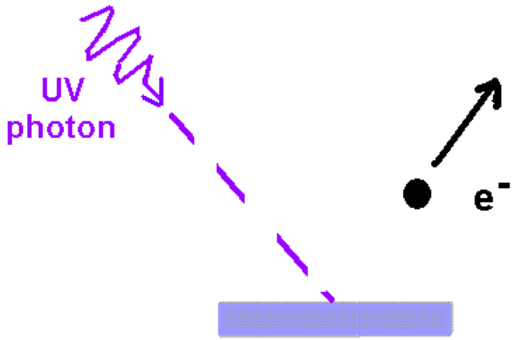
This appears to support the particle nature of light. Since we view electrons as particles, the light coming in can be understood as tiny cue balls that are bumping out the billiard balls (the electrons).



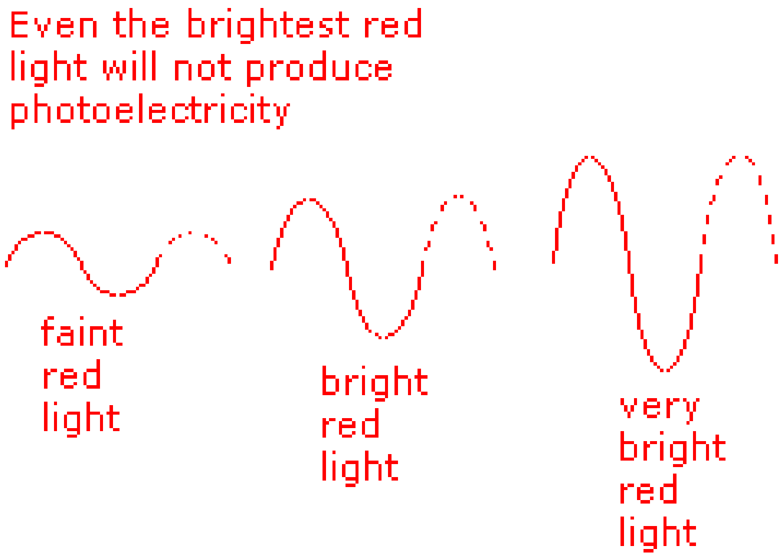
Each photon carries *hf* amount of energy, and the energy from one photon transfers to one electron when it hits the surface of the material. The electron then uses this energy to escape the forces holding it in the material's structure, and is emitted with an associated kinetic energy.

Einstein applies Planck's quantum idea to photoelectricity

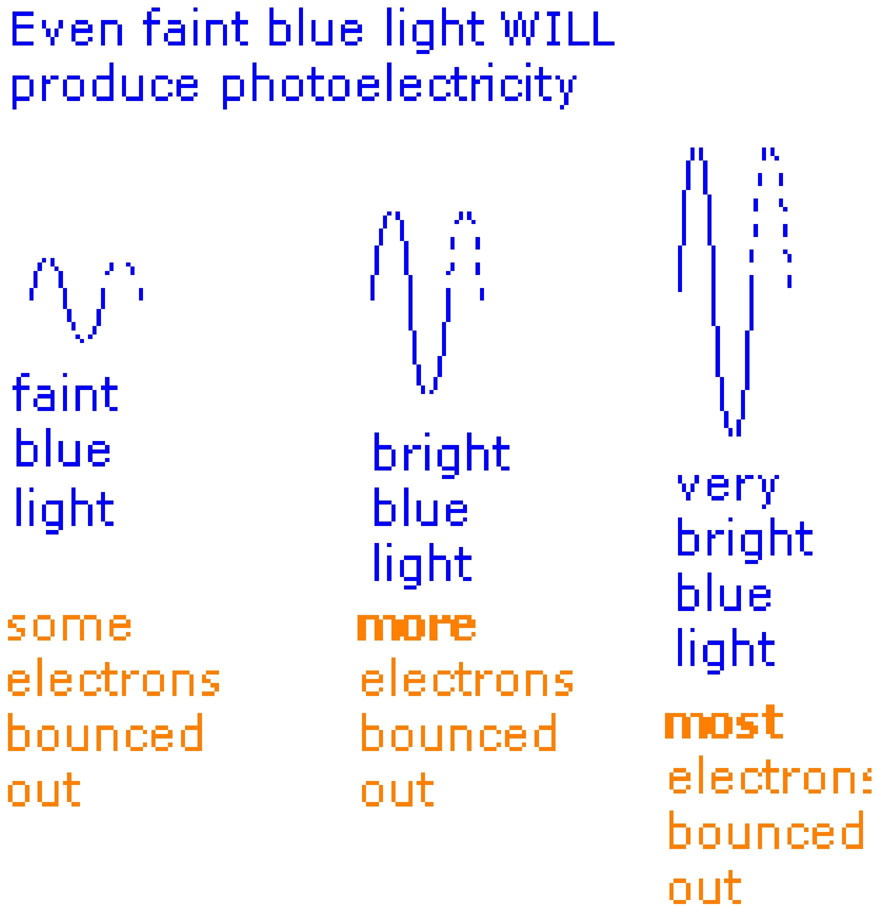
Remember, the photoelectric effect occurred when light struck a metal and electrons were bounced out. However this does not happen for just any light. For example, it will not happen for red light. No matter how bright the red light, it still won't bounce the electrons out.



It is the amplitude that illustrates the brightness, and varying the light still will not cause the photoelectric phenomenon.



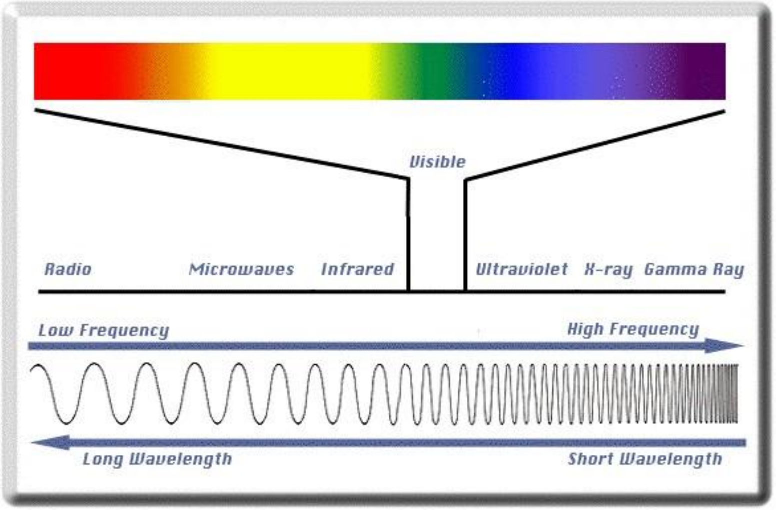
The picture show three different brightness's of blue light. Now the story is quite different. Even the faintest blue light knocks electrons from the metal plate. As the light becomes brighter, more and more electrons are emitted



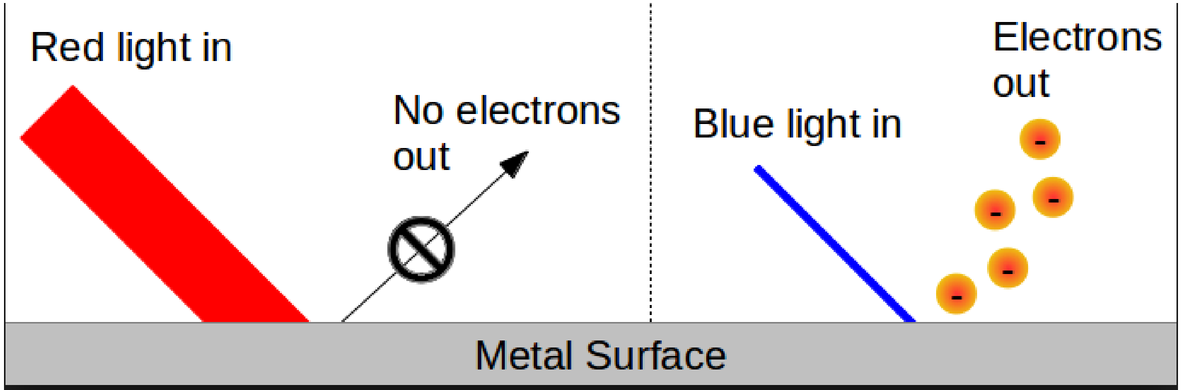
Why does this happen?

1) **It's the frequency that governs the energy of the in-coming light.**

Check the electromagnetic spectrum and you'll see that blue light has a higher frequency than red.

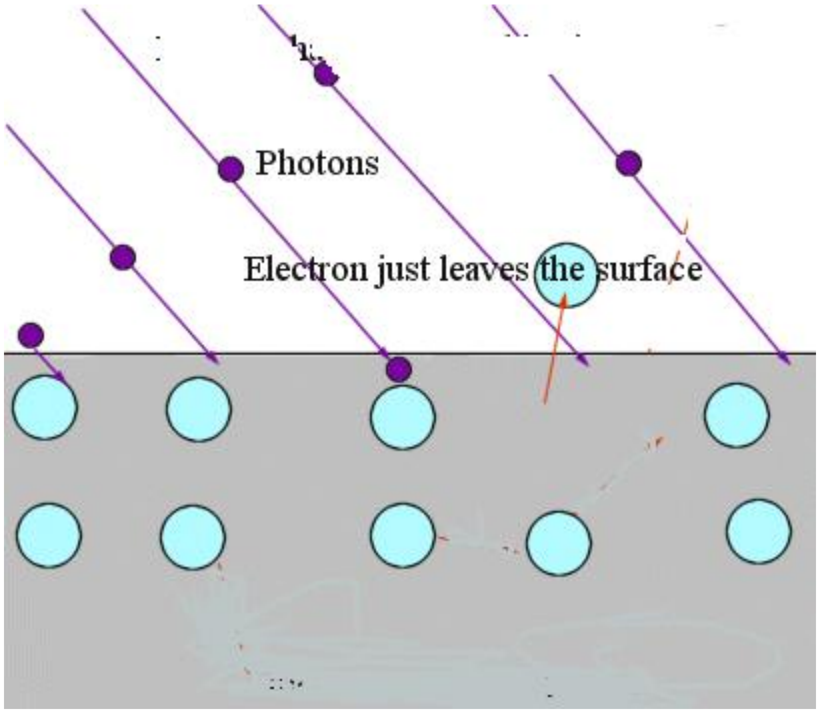


Therefore, photons of blue light have more energy to eject electrons than red.

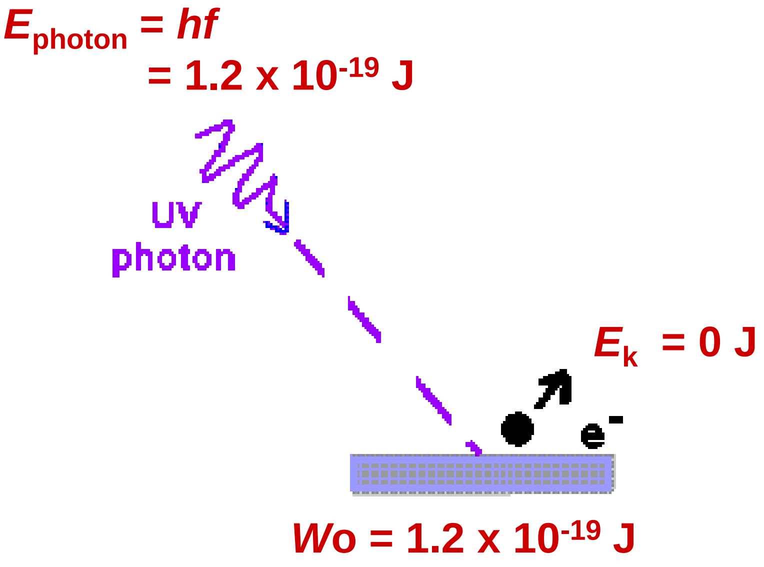


Threshold Frequency or Cut Off Frequency

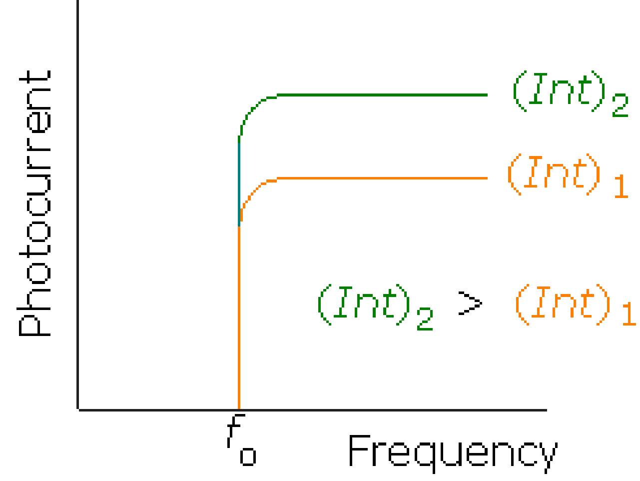
Threshold frequency or cut off frequency (f_o) is defined as the minimum frequency of incident light which can cause photo electric emission i.e. this frequency is just able to eject electrons with out giving them additional energy.



If the frequency of the impinging light is less than f_o, then no electrons will be liberated. When $f = fo$ the electrons are just barely liberated. All of the photon energy is used up in the work function (W_o) just to break them free and no energy is left over to give the electrons kinetic energy.



The photocurrent graph results from light of two different intensities (*Int*)$_1$ and (*Int*)$_2$ being shone on the same material. (*Int*)$_2$ > (*Int*)1 .

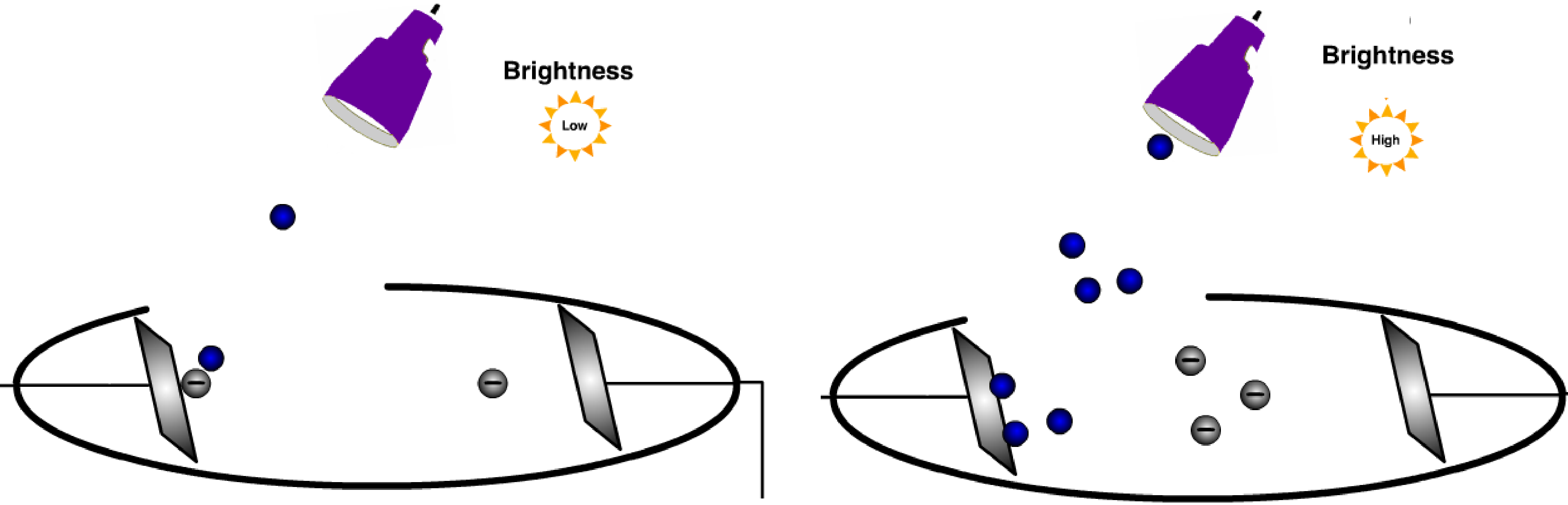


1. If the frequency of the light is less than f_o (the cut-off or threshold frequency), then no electrons will be liberated. When $f = f_o$ the electrons are just barely liberated.

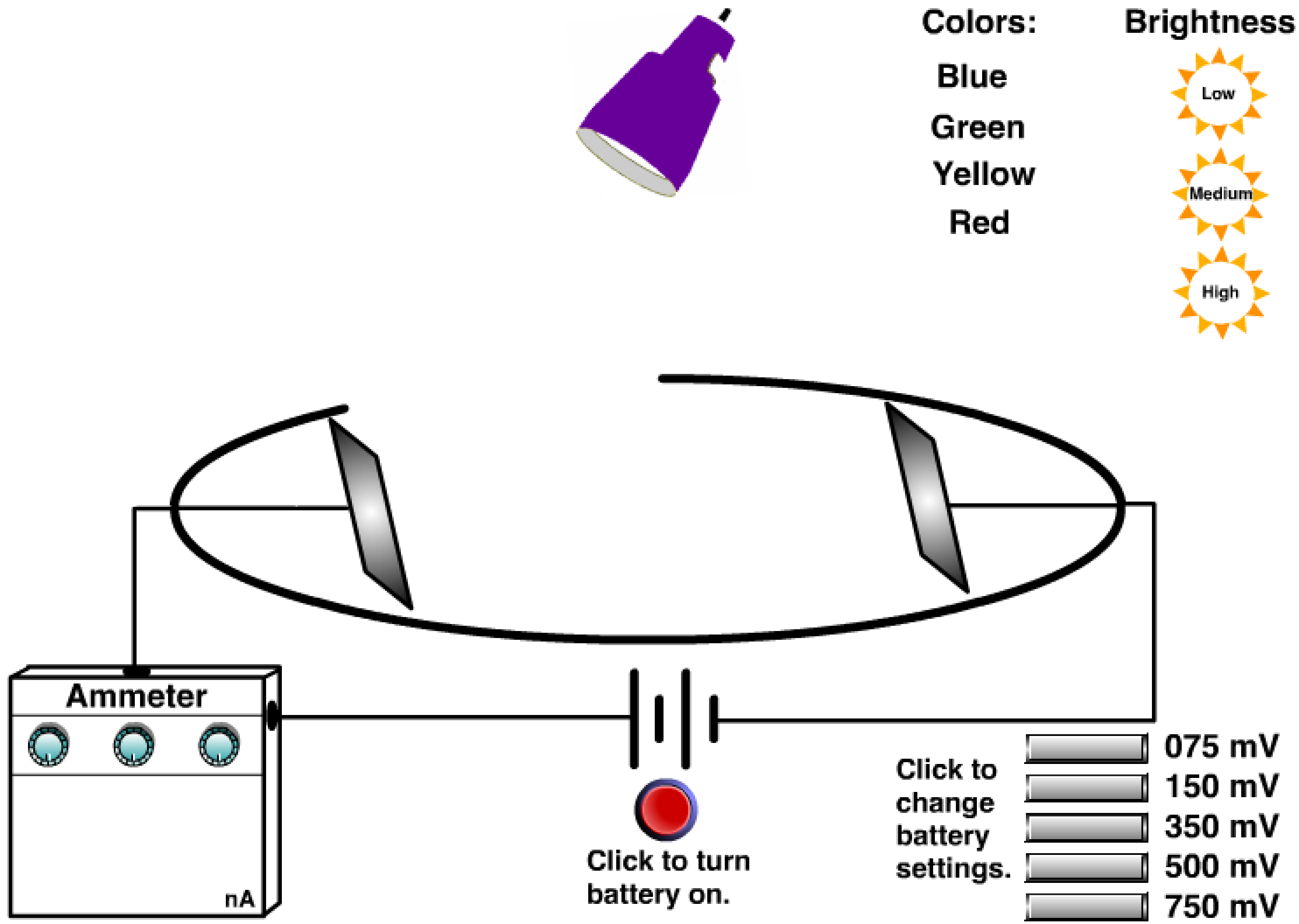
2. Once the threshold frequency has been exceeded, the current jumps to a maximum value. But for each light intensity the current will be constant as shown by the horizontal orange and green parts of the graph.

3. For a particular intensity, the size of the current does not depend on the frequency of the in coming photons. Increasing the frequency does not increase the size of the current, but it does increase the energy of each emitted electron.

The brighter the light, the more the photons, and each photon knocks out one electron.



the photoelectric effect provides very good evidence that light is composed of tiny packets/bundles/**quanta** of energy.


Colors:
Blue
Green
Yellow
Red
Brightness
Low
Medium
High
Ammeter
nA
Click to turn battery on.
Click to change battery settings.
075 mV
150 mV
350 mV
500 mV
750 mV

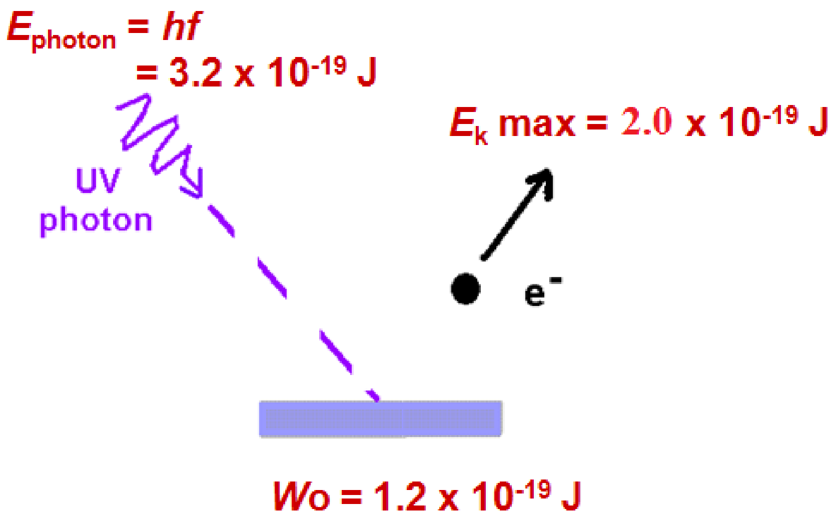
The photoelectric effect can be explained in terms of the conservation of energy :

photon energy = work done in releasing the electron + kinetic energy of electron

$$E_{photon} = W_o + KE_{electron}$$

$$hf = W_o + \frac{1}{2} m_e v^2$$

$$h\frac{c}{\lambda} = W_o + \frac{1}{2} m_e v^2$$



Example 1:   Photoelectric effect

A 2.72×10^{15} Hz photon acquires 1.1×10^{-18} J of kinetic energy. What is the work function of the metal? JUNE 2004

Example 2: Photoelectric effect

An emitted photon of 122 nm hits a photocell, inducing the photoelectric effect. If the work function of the metal is 3.68×10^{-19} J, what is the maximum kinetic energy of the emitted electron? JUNE 2005

Example 3: Photoelectric effect

Light is incident on a metal that has a work function of 2.28 eV. If the maximum kinetic energy of the emitted electrons is 2.34×10^{-20} J, calculate the wavelength of the incident light. AUGUST 2007

Example 4: Photoelectric effect

A certain metal with a known work function of 2.8 eV is shone with light of wavelength 625 nm. Will the photoelectric phenomenon be observed?

Solution

The incoming photons must have enough energy to free the electrons from the surface. That is, E_{photon} must be at least equal to the work function *W*o.

*W*o = 2.8 eV

λ = 625 nm = 625 x 10^{-9} m = 6.25 x 10^{-7} m

h = 6.63 x 10^{-34} J·s c = 3.00 x 10^{8} m/s

We will calculate E_{photon} from $\mathbf{E_{photon} = hf = (hc)/\lambda}$ and then compare with W_o.

From Planck's equation, $E_{photon} = hf = (hc)/\lambda$

= (6.63 x 10^{-34} J·s x 3.00 x 10^{8} m/s) / 6.25 x 10^{-7} m

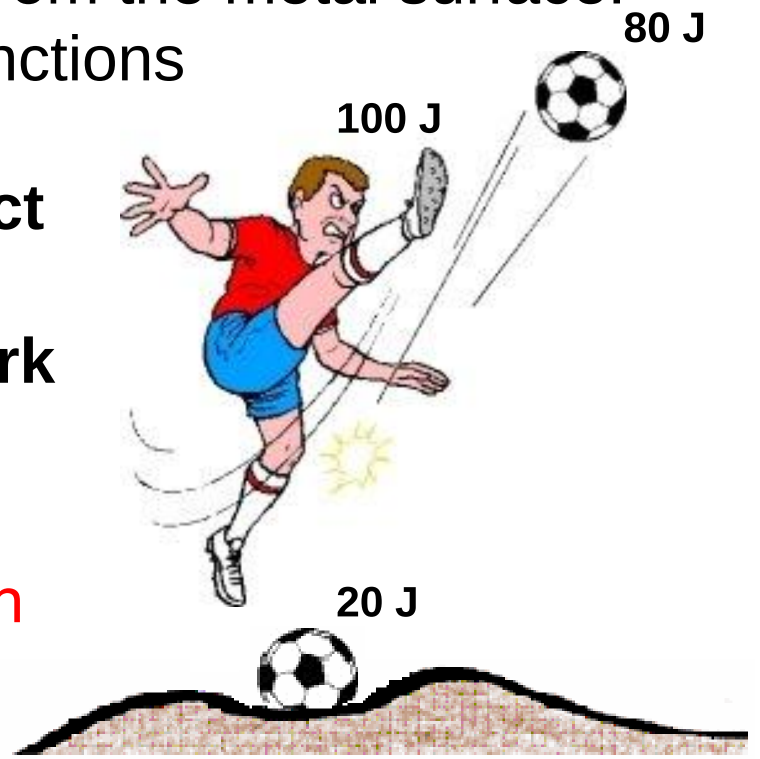
= 3.2 x 10^{-19} J

Change 3.2 x 10^{-19} J into eV by dividing by 1.6 x 10^{-19} J/eV to get *E*photon = 2.0 eV.

The work function is given to be 2.8 eV. $E_{photon} < W_o$ Therefore no electrons will be liberated.

The work function (W_O)

The **Work function (W_O)** refers The minimum energy, E, required to release the photoelectron from the metal surface. Different metals have different work functions



Therefore, for the photoelectric effect to occur, the energy of the incident photon must be greater than the work function: $E_{photon} > W_o$

If the photon's energy, E, is just enough to release a photoelectron, then its frequency is called the threshold frequency (f_0):

Remember the photoelectric effect can be explain in terms of the conservation of energy

$$\text{photon energy} = \begin{matrix}\text{work done in releasing} \\ \text{the electron}\end{matrix} + \begin{matrix}\text{kinetic energy} \\ \text{of electron}\end{matrix}$$

If a photon's hits the metal with the threshold frequency (f_0):, the emitted electron will have no kinetic energy. Therefore, the formula is rewritten as:

$$\text{photon energy} = \begin{matrix}\text{work done in releasing} \\ \text{the electron}\end{matrix}$$

$$E_{Photon} = W_o$$

$$hf_o = W_o$$

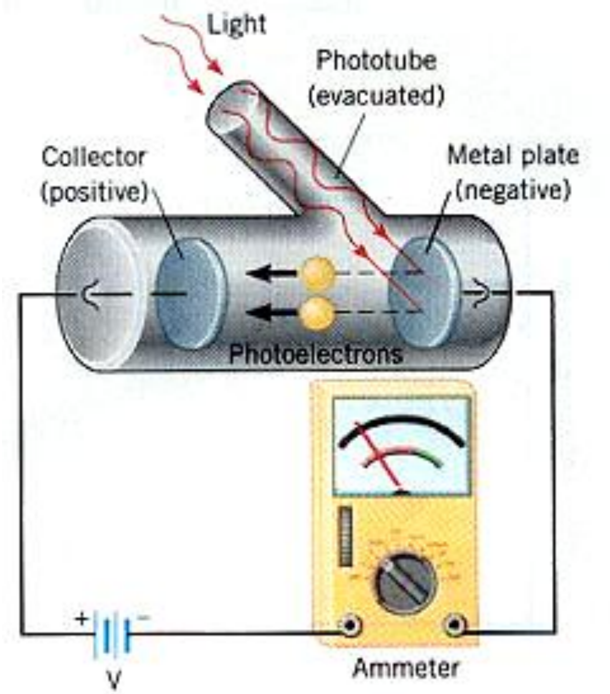
Example 5: Photoelectric Effect -Threshold Frequency

Determine the threshold frequency of a material with a work function of 10eV.

Example 6: Photoelectric Effect Threshold Frequency

Calculate the maximum wavelength that will cause photoelectric emission from a metal surface having a work function of 2.00 eV.

Stopping Potential



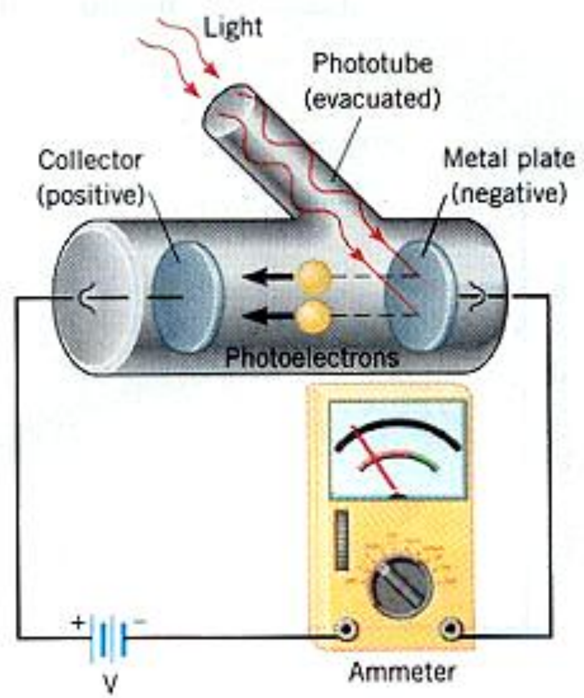
The voltage source in the external circuit makes the collector plate positive, causing the electrons to stream across to the collector plate.

If the voltage source in the external circuit is reversed, the collector plate will become negative. Now the electrons that are being bumped out of the metal plate will be slowed down because now the collector plate is also negative.

If the voltage (or potential) is increased (That is, if the collector plate is made more negative), the electrons will finally stop coming across.

The reverse voltage or reverse potential that prevents photoelectrons from moving to the collector plate is called **Stopping potential** (V_{stop}).

The electrons have **Kinetic energy** while they are moving. As they are forced to stop they have Potential energy (Think of a rock that is thrown into the air and brought to a stop by gravity.)



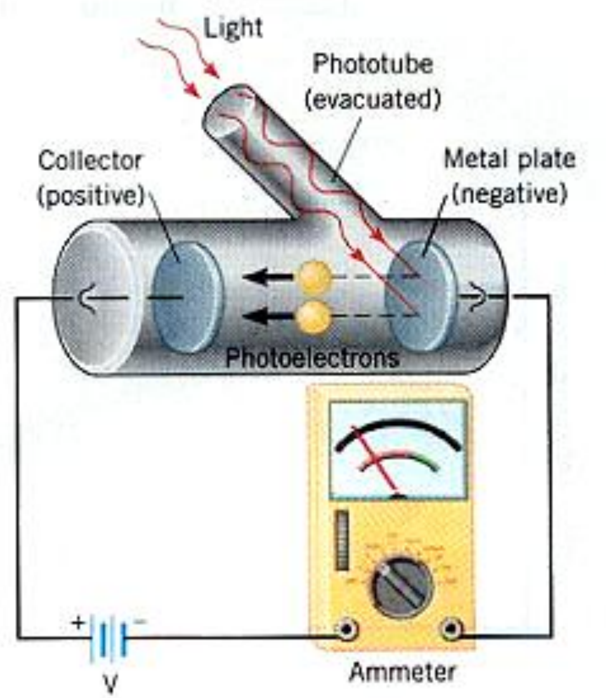
According to the law of conservation of energy, the kinetic energy that has "disappeared" and the potential energy that has taken its place must be equal!

The total kinetic energy (E_k max) that each electron had is converted to electrical potential energy (E).

Remember from last unit that :

electric potential energy: is $E = qV$ which, for a single

For an electron, is $E = eV$.



So the electric potential energy of an electron that has just been stopped is $E = eV_{stop}$ and this is equal to the kinetic energy that the electron use to have.

$$KE_{max} = eV_{stop} \,.$$

$$\frac{1}{2} m_e v_{max}^2 = eV_s$$

Example 7

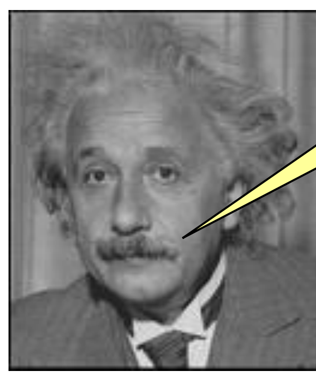
When an ultraviolet wave with wavelength 126 nm strikes a certain metal, the reversing or stopping potential that brings the photoelectric current to 0 is 4.2 V. Use Table 17.1 on p. 704 to determine the type of metal in the emitter plate.

Example 8

When light having frequency 3.0×10^{15} Hz is shone on a certain metal, electrons are ejected. If the stopping potential of these electrons is 7.0 V, calculate the work function of this metal.

Einstein (in 1905) showed that the photoelectric effect could be understood if light were thought of as a stream of particles (photons) with energy equal to hf.

I got my Nobel prize for that.



Summary of photoelectric effect:

- Is the emission, or ejection, of electrons from the surface of, generally, a metal in response to incident light.

- support the particle nature

- Can be summarized in the following formula:

$$\text{photon energy} = \begin{array}{c}\text{work done in releasing}\\ \text{the electron}\end{array} + \begin{array}{c}\text{kinetic energy}\\ \text{of electron}\end{array}$$

- Two special cases

1) The threshold Frequency

$$E_{Photon} = W_o$$

2) The Stopping Potential

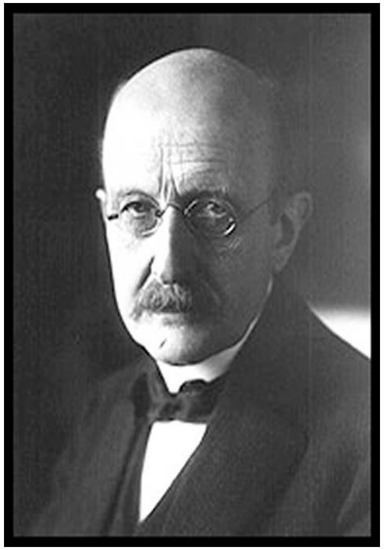
$$KE_{max} = eV_{stop}$$

Einstein proposed the photoelectric effect as a test of Planck's quantum hypothesis. Einstein proposed that light also delivers its energy in chunks; light would then consist of little particles, or quant called photons, each with an energy of Planck's constant times its frequency.

Wave-Particle Duality

The results of the photoelectric effect allowed us to look at light completely different. (***more on this later!***)

First we have Thomas Young's Diffraction experiment proving that light behaved as a WAVE due to constructive and destructive interference.



Then we have Max Planck who allowed Einstein to build his photoelectric effect idea around the concept that light is composed of PARTICLES called quanta.

When Data doesn’t match theory…

- **<u>Classical physics</u>** predicts that ***any frequency of light*** can eject electrons as long as the intensity is high enough.
- **<u>Experimental data</u>** shows there is ***a minimum (cutoff frequency) that the light must have***.
- **<u>Classical physics</u>** predicts that ***the kinetic energy of the ejected electrons should increase with the intensity of the light***.
- Again, **<u>experimental data</u>** shows this is not the case; ***increasing the intensity of the light only increases the number of electrons emitted, not their kinetic energy.***
- THUS the photoelectric effect is strong evidence for the photon model of light.


CONSTANTS
SPEED OF LIGHT: c
GRAVITY: G
ELEMENTARY CHARGE: e
1ST RADIATION CONSTANT: 8πhc
MASS UNIT: u
ELECTRON MASS: me
PROTON MASS: mp
NEUTRON MASS: mn
ELECTRON RADIUS: re
GAS CONSTANT: R
S. Harris

Video: PHOTOELECTRIC EXPERIMENT (3 min)
APPLICATIONS OF PHOTOELECTIC EXPERIMENT (3 min)

In your textbook:

on p. 707, do #1--#4

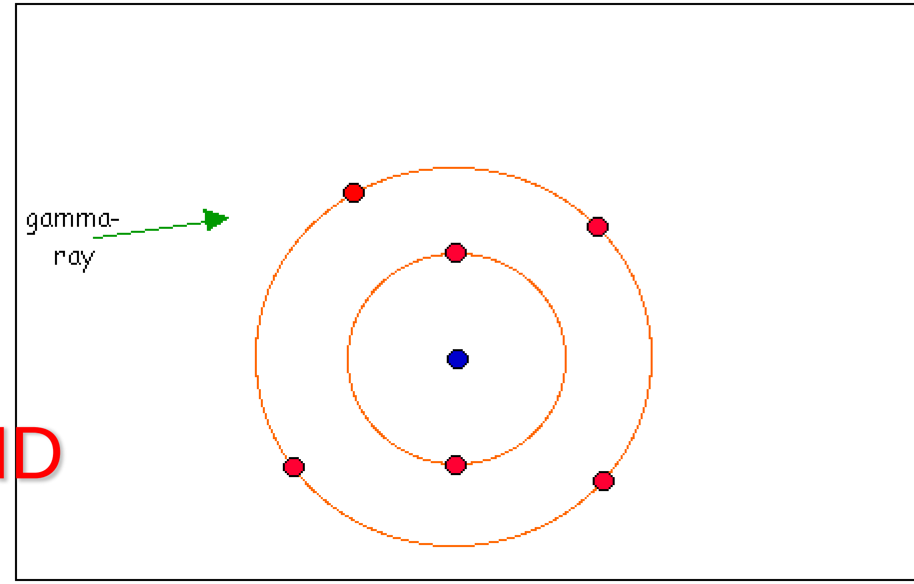
on p. 731, do #7

on p. 732, do #23--#24, #26--#29

STSE The Physics of Movie Sound

Physics 3204

UNIT 3: Section 3



THE COMPTON EFFECT AND PHOTON MOMENTUM

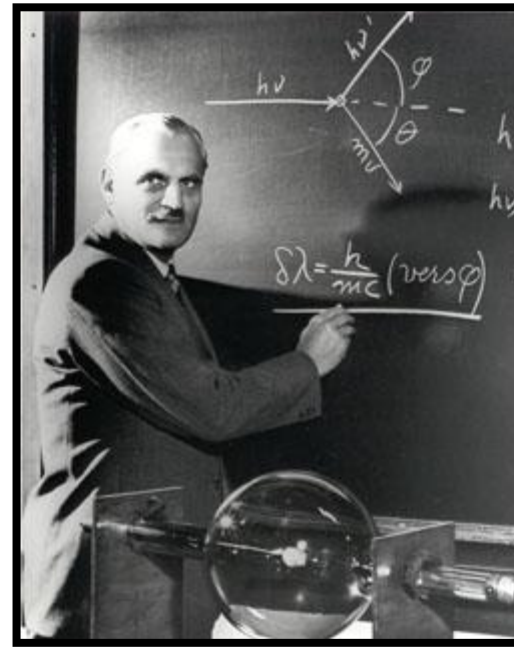
AND

DE BROGLIE AND THE WAVE NATURE OF MATTER

Text Reference:
17.4-17.5

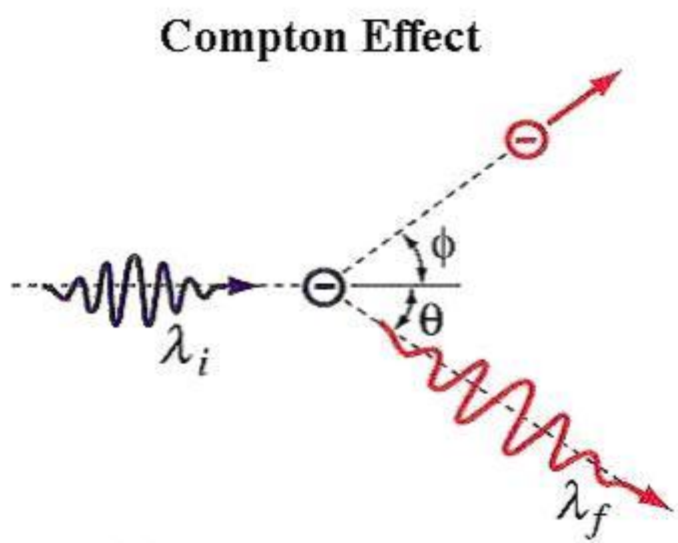
"Oh, and I suppose it was me who said 'what harm could it be to give the chickens a book on nuclear physics?' "

A fellow named Arthur Holly Compton one day decided that he would shoot a few x-rays at a metal target.



After the target was struck, he noticed that it emitted: electrons but also some other x-rays!

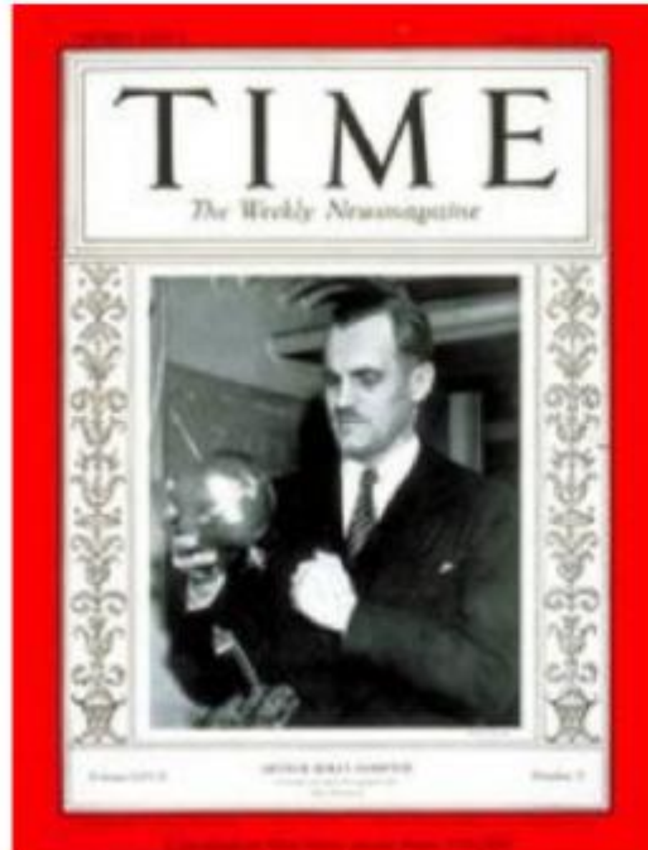
He discovered that the second lot of x-rays had lower energy than the incident x-rays.



This phenomenon is called the **Compton Effect or Compton Scattering**.

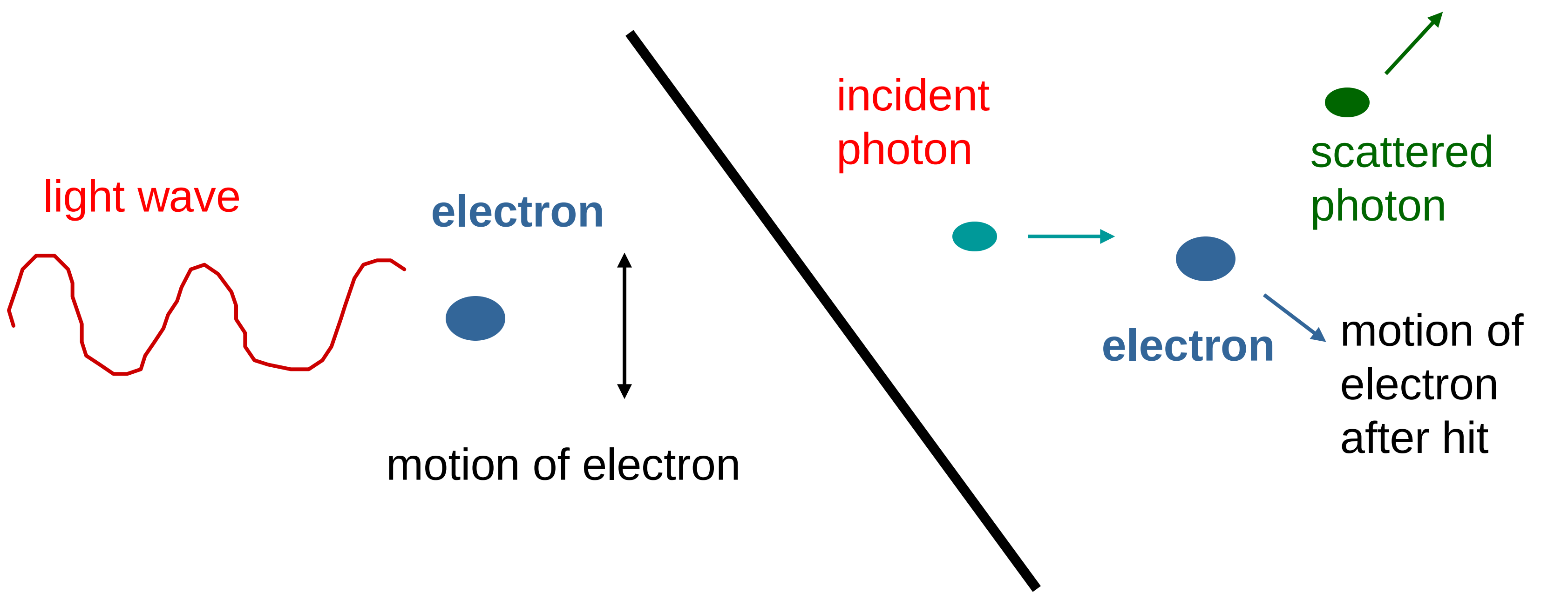
Proof = Arthur Compton

In 1923, 18 years after Einstein's Wonderful Year (and after all his other theories from that year had been proven), American Arthur Compton devised an experiment to show photons have momentum.



Compton Effect

- When light encounters charged particles, the particles will interact with the light and cause some of the light to be scattered.



- From the wave theory, we can understand that charged particles would interact with the light since the light is an electromagnetic wave!

- But the actual predictions of how the light scatters from the charged particles **does not fit our simple wave model**.

- If we consider the **photon idea** of light, some of the photons. would "hit" the charged particles and "bounce off". The laws of conservation of energy and momentum should then predict the scattering.

Compton : Momentum and Photons:

Light, as a wave, should not have momentum, since momentum requires p = mv.

However, Compton’s work showed that photons collide and exchange energy with particles according to the law of conservation of energy, that they possess momentum, and that this momentum is conserved during a collision.

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

p= momentum of photon

λ = wavelength of light

Plank`s Constant = 6.626 x 10 -34 Js

Example 1

An electric stove produces many infrared electrons. If the peak wavelength of the radiation coming from a stove is 10 μm, what is the momentum of the released photons ?

Example 2

Calculate the momentum of a photon whose frequency is 5.00×10^{14} Hz.

Example 3

Calculate the wavelength of a photon whose momentum is 5.00×10^{-25} kg.m/s.

Example 5

Calculate the energy of a photon whose momentum is 2.50×10^{-25} kg.m/s.

Example 6

Calculate the frequency of a photon whose momentum is 2.50×10^{-25} kg.m/s.

Louis de Broglie

Louis de Broglie noticed that sometimes physics ideas are reversible. For example, we have already seen how changing electric fields produce magnetism (Oersted) and changing magnetic fields produce electricity (Faraday).

After Compton showed that electromagnetic radiation (photons) exhibited properties of mass (i.e., momentum), de Broglie wondered if mass might have wave properties.

De Broglie argued that if light sometimes behaves like a wave and sometimes like a particle , then perhaps those things in nature thought to be particles – such as electrons and other material objects – might also have wave properties

Louis de Broglie (in 1923)

If light can behave both as a wave and a particle, I wonder if a particle can also behave as a wave?

De Broglie : Matter Waves:

In 1924, the French physicist Louis de Broglie proposed that moving objects behave like waves; these are called **matter waves**.

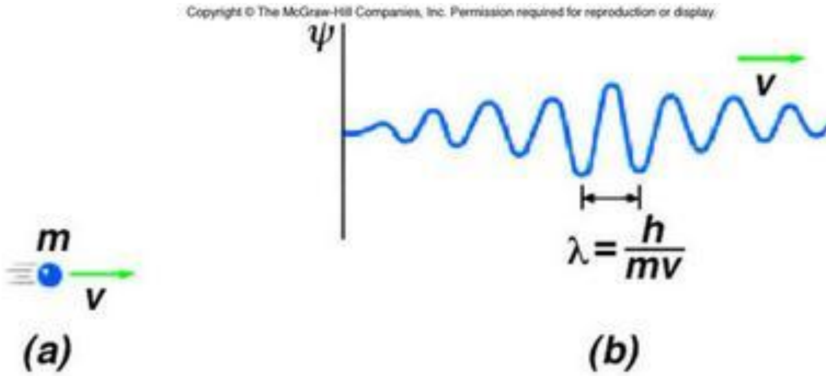
De Broglie built on the work of Compton by proposing that since waves can act like matter, perhaps matter can be described as a wave..

Compton's equation from the last lesson: $p = h/\lambda$

De Broglie's rearrangement: $\lambda = h/p$

But p = momentum = mass x velocity = $m v$

Therefore, $\lambda = h/m v$.



De Broglie : Matter Waves formulae:

De Broglie wavelength depends on the mass *m* and speed *v* is the particle

$$\lambda = h/p$$

or

$$\lambda = h/m\,v.$$

All matter, baseballs, humans and cats named Sue, can be through of as having a wavelength, but it is so incredibly small that it is not noticeable.

You knew this day would come… If Broglie can do it so can I.

The Mr. Fifield

After using the equation F=mg for years. Mr. Fifield wondered if it would hold true for mass. He rearranged the force equation.

The force equation, $F = mg$

Fifield's rearrangement: $m = f/g$ Units (the Mr. Fifield)

Example 1

If your mass was 70 kg, find your associated wavelength when you are running at 8.0 km/hr (2.2 m /s).

Solution

$\lambda = h / m v = 6.63 \times 10^{-34}$ J· s ÷ (70 kg x 2.2 m /s)

$= 4.3 \times 10^{-36}$ m.

As you can see, we haven't proven very much. Even if you do have wave properties when you are moving, the wave is so small that there is no way to detect it.

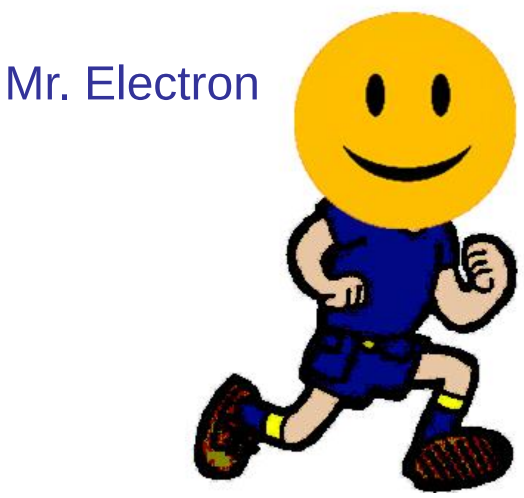
Example 2

The mass of an electron is 9.11×10^{-31} kg. At what speed would an electron have a de Broglie wavelength of 540 nanometers?

Mr. Electron

Example 3

Calculate the de Broglie wavelength of a helium nucleus (mass = 6.7 x 10-^{27} kg) moving with a speed of 2.0 x 10^6 m/s



Test yourself

h = 6.63 x 10-34 J·s
m_e = 9.11 x 10^{-31} kg

1. Which of the following would have the smallest associated de Broglie wave if the objects all have the same speed?
a) neutron b) green pea c) grape d) orange

2. As a particle slows down, what happens to its de Broglie wavelength?
a) goes to zero b) increases c) decreases d) remains constant

3. An electron has an associated de Broglie wavelength of 0.36 nm. How fast is it moving?
a) 2.0 x 10^{6} m /s b) 5.0 x 10^{-7} m /s c) 5.0 x 10^{7} m /s
d) 2.0 x 10^{-6} m /s

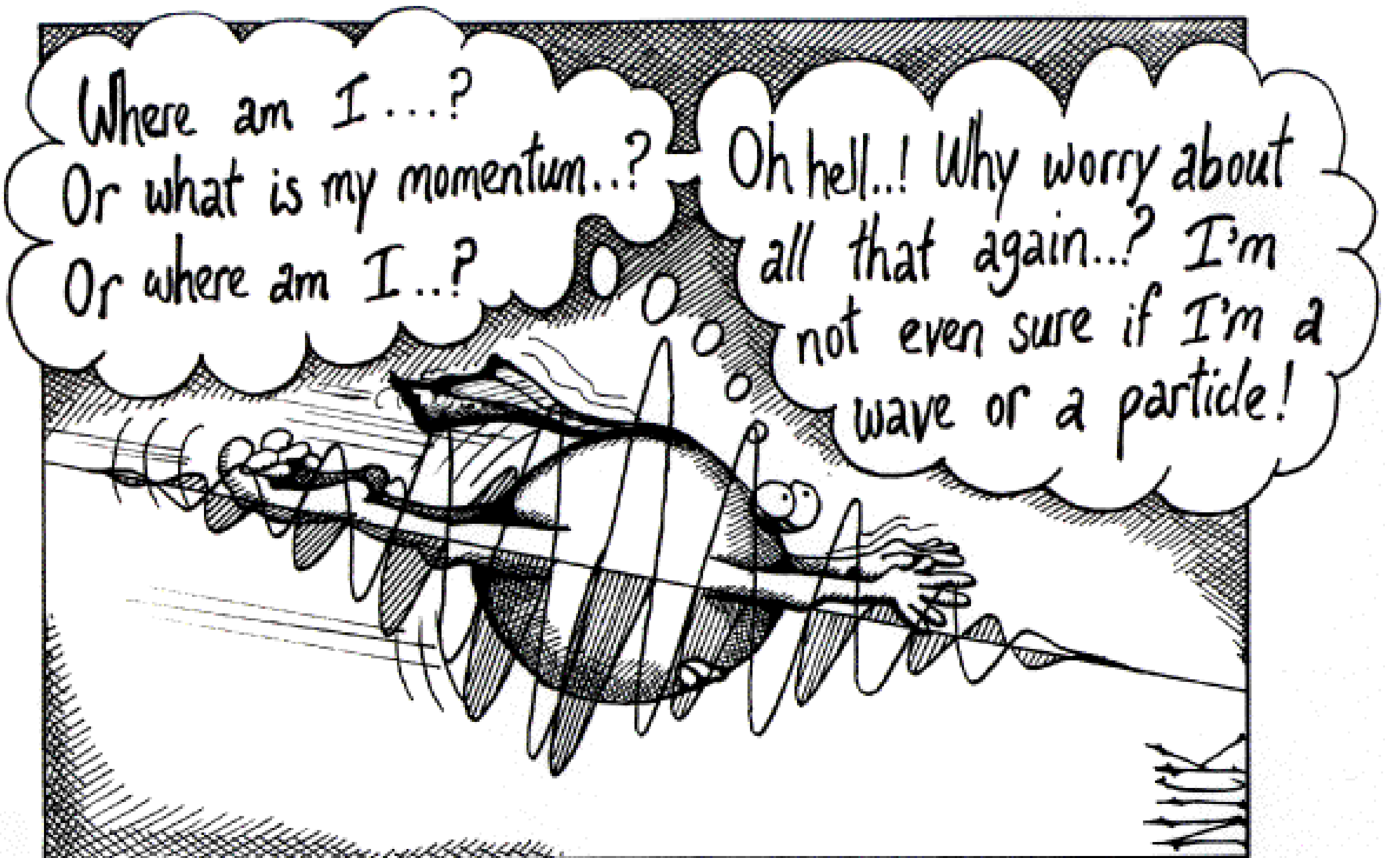
4. What is the de Broglie wavelength of an electron with a kinetic energy of 40 e V?
a) 0.78 nm b) 0.83 nm c) 0.19 nm d) 0.91 nm

5. How much energy in electron volts (e V) must be given to an electron in order that its associated de Broglie wavelength be 0.38 nm?
a) 40 eV b) 30 eV c) 20 eV d) 10 eV

Answers

1. d--$\lambda = h/mv$ and the orange has the largest mass.
2. b--because $\lambda = h/mv$ and v is in the denominator.
3. a--solve $\lambda = h/ m v$ for v: $v = h/ m\lambda$.
4. c--change 40 e V to J. Find v from E k = ½ mv2. Then find λ from $\lambda = h/ m v$. Change 1.9×10^{-10} m to 0.19 nm.

5. d--find v from $\lambda = h /m v$. Find kinetic energy from E k = ½ mv^2. Change J into e V by dividing by 1.6×10^{-19}.



= PHOTON SELF-IDENTITY PROBLEMS =

De Broglie and the Wave Nature of Matter

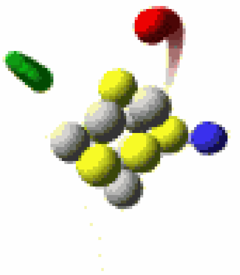
Assigned activities

In your text:
on p. 712--do #1
on p. 732-733--do #36--39

See handout: The Compton Effect and Photon momentum

Video: Compton effect (

Physics 3204



UNIT 3: Section 4

BOHR'S APPLICATION OF QUANTA

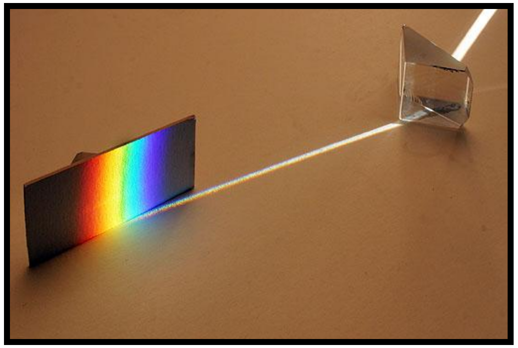
Text Reference:
17.6

Spectra

Spectrum refers to when light is spread out into its separate colours.

Consider the following spectra:

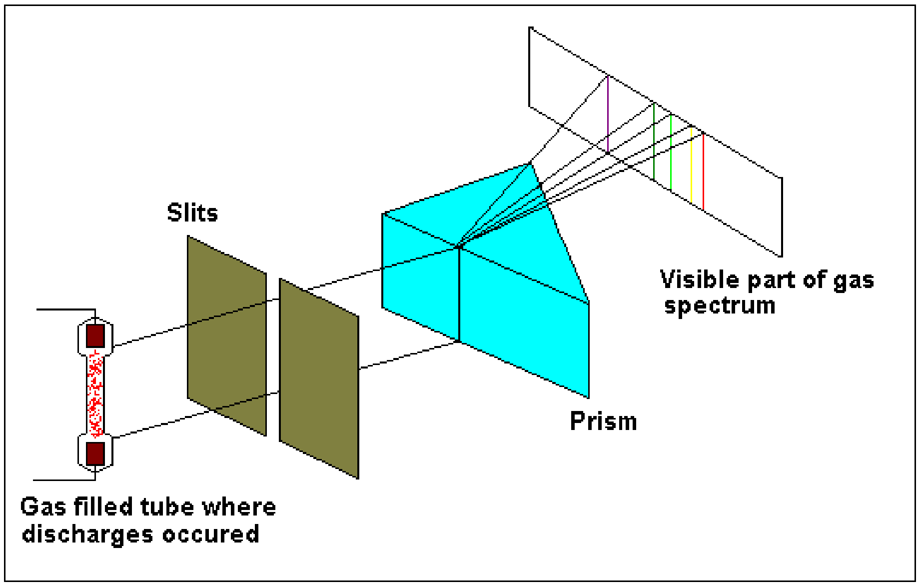
1) **Continuous Spectrum:** coloured band with one colour merging into another.



2) **Line spectrum:** you will see distinct coloured lines.

Spectroscope;

Spectroscope - An instrument designed for visual observation of spectra



Discharges in the low - pressure gas filled tube are sources of light, which undergo refraction on a prism. We see the line spectrum of the gas.

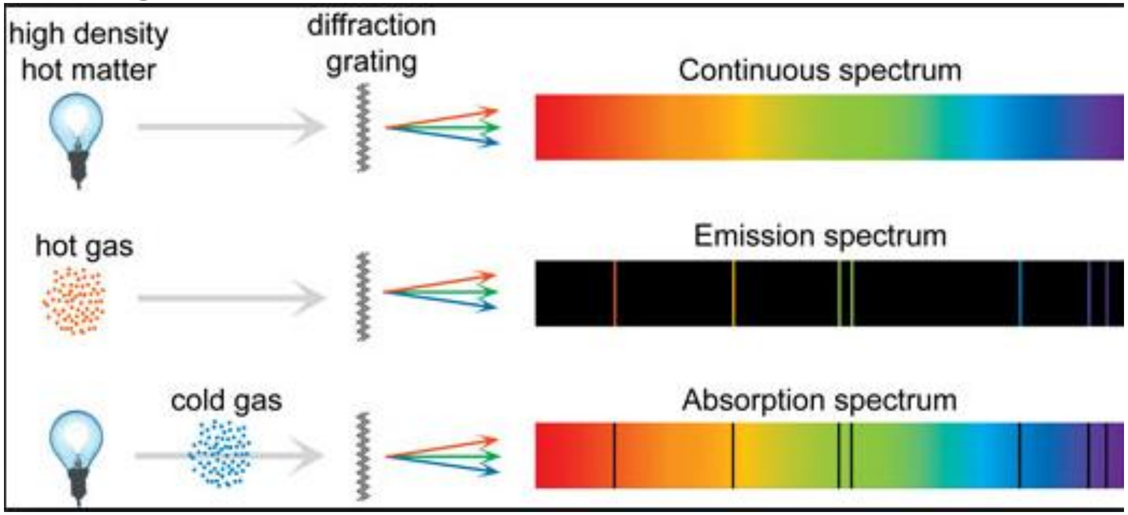
The gas is enclosed in a glass container and electricity is passe through it. The electricity "excites" the atoms, the electrons are repeatedly bumped to high levels and fall back to lower orbits at which point they emit radiation. We see the radiation as a glow. The glow is passed through lenses, a slit, a prism or diffraction grating, and we see the lines mentioned earlier. The lines are actually images of the slit.

Spectra may be classified according to the nature of their origin

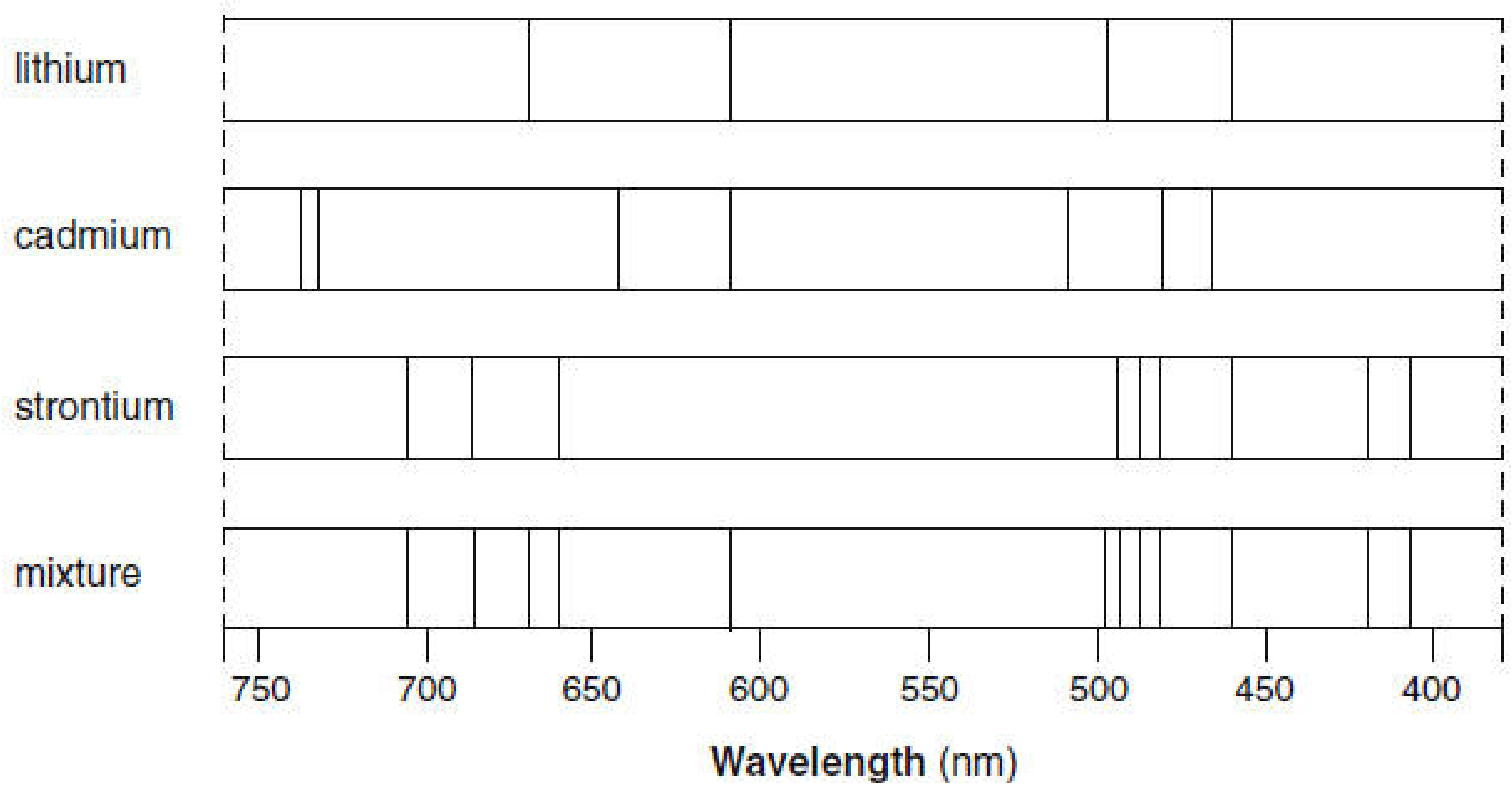
Continuous Spectra: When an element is heated to incandescence. It is continuous because all wavelengths are present

Emission spectra - the spectrum lines which are created from an excited gas.

Absorption spectra - the dark lines which are observed when a continuous spectrum passes through a gas. These lines have the same wavelength as the emission lines from that gas



For a given gas, the lines are always of the same wavelength, like an atomic fingerprint!



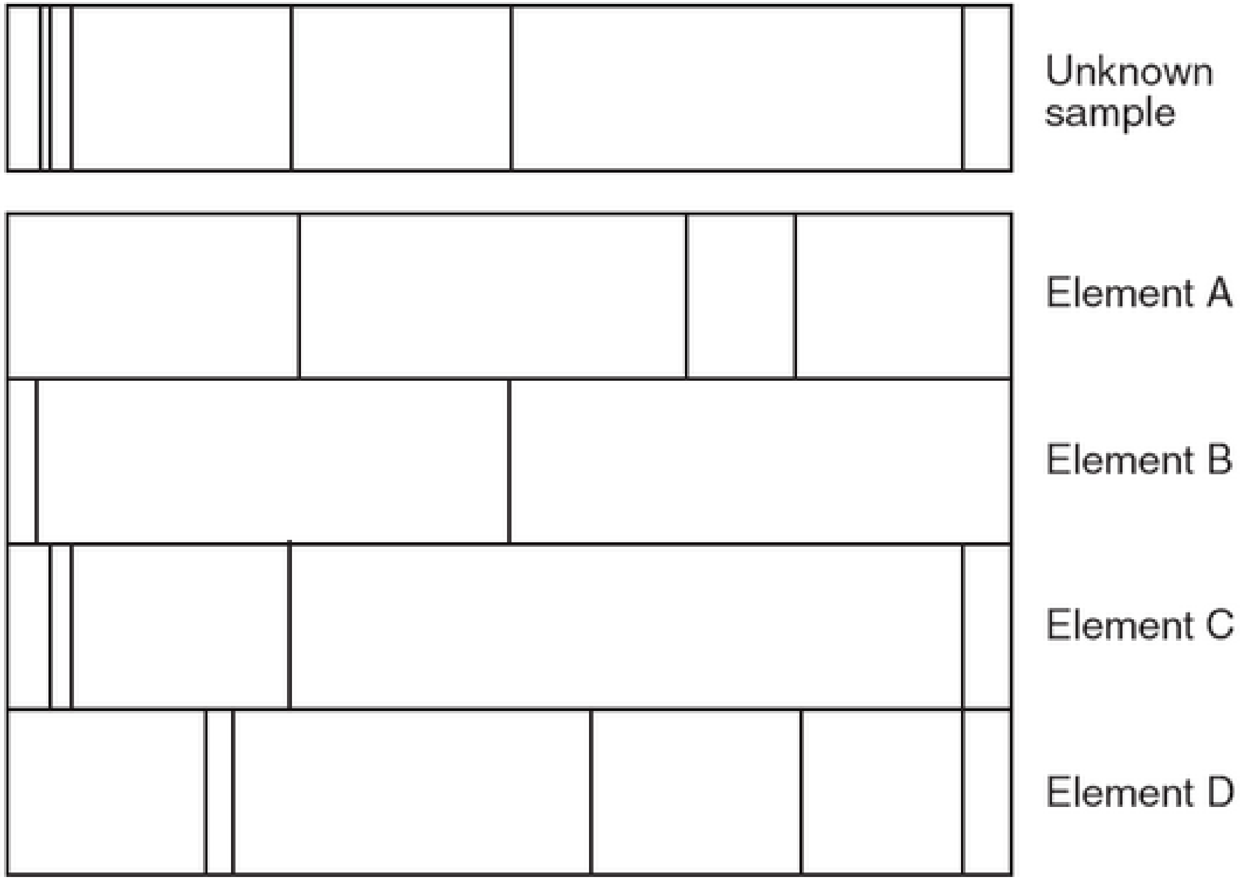
This knowledge is very useful to chemists and other scientists. Why?

Spectral lines used to:

1) identify unknown elements.

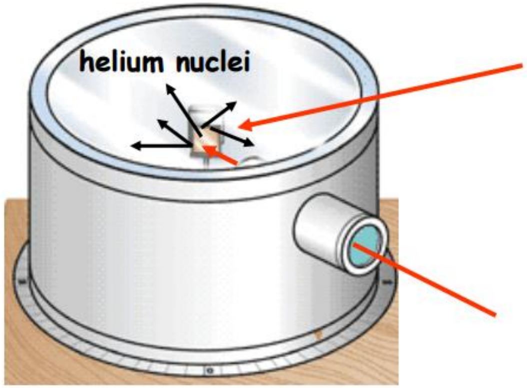
2) determine the composition of distant stars

Based on comparisons of these spectra, which two elements are found in the unknown sample?



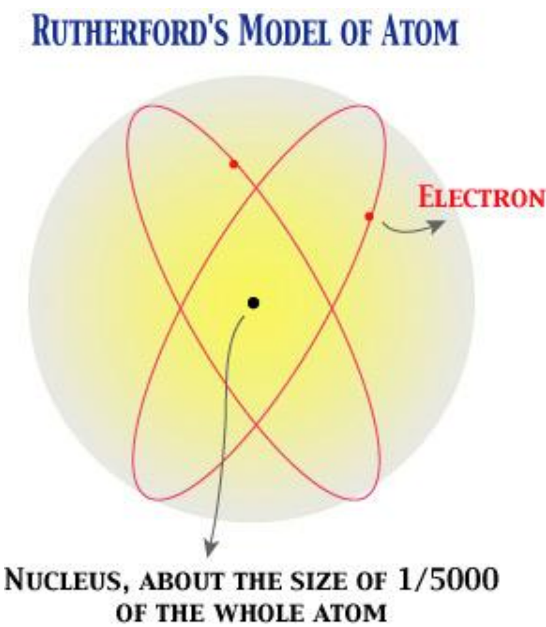
Rutherford’s Model-Nuclear Model

Rutherford’s model was based on observations of firing Helium nuclei at a piece of gold foil which was only a few atoms thick.



In 1911, **Rutherford proposed his model of the atom**, based on the results of many such scattering experiments.

He proposed that the atom consisted mainly of empty space with a tiny, positively charged nucleus, containing most of the mass of the atom, surrounded by negative electrons in orbit around the nucleus like planets orbiting the sun.



Problems with Rutherford's Model

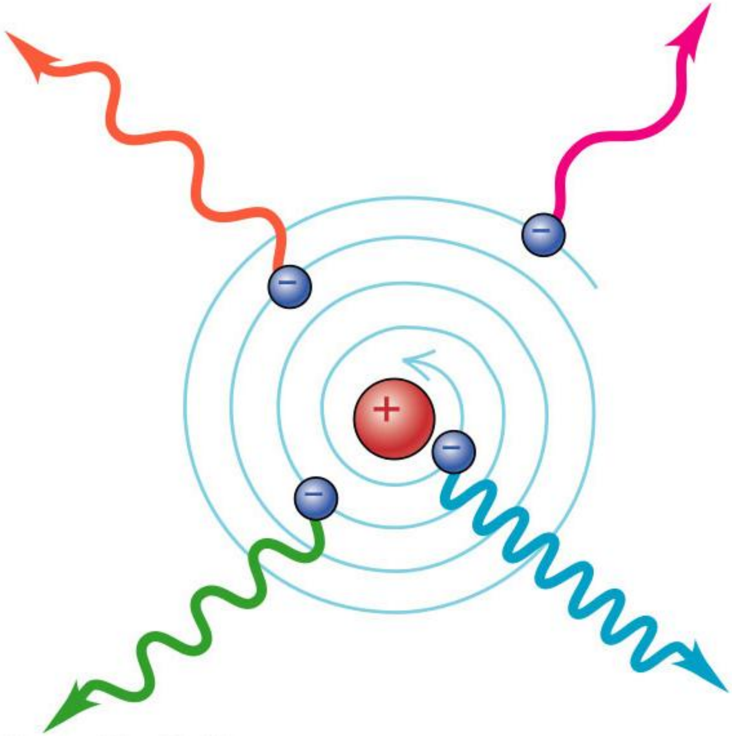
Problem #1

Since the electrons were in circular motion, **should be emitting electromagnetic radiation**. This loss of energy would cause the electrons to gradually spiral closer and closer to the nucleus and to eventually crash into the nucleus. Thus, **matter would be very unstable**. This was clearly not the case.

Problem #2

Rutherford's model could not explain the observed **line spectra of elements**. As electrons spiraled towards the nucleus with increasing speed, they should emit all frequencies of radiation not just one. Thus, the observed spectrum of the element should be a **continuous spectrum** not a **line spectrum**

Failure of the Classical model



The orbiting electron is an accelerating charge.

Accelerating charges emit electromagnetic waves and therefore lose energy

Classical physics predicts electron should “spiral in” to the nucleus emitting continuous spectrum of radiation as the atom “collapses”

CLASSICAL PHYSICS CAN’T GIVE US STABLE ATOMS………………..

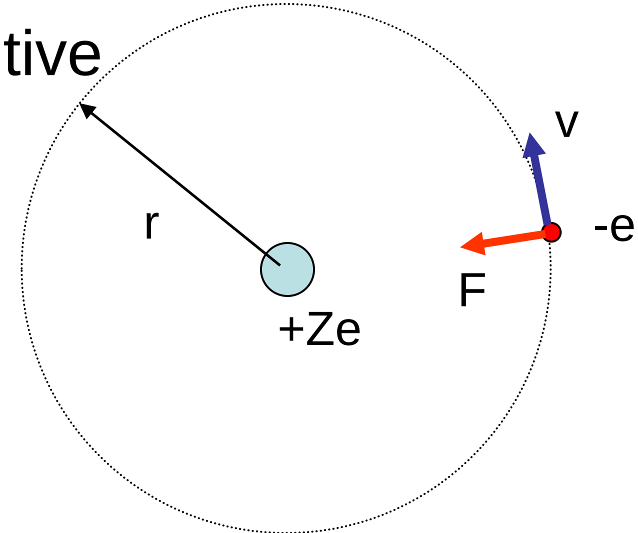
Niels Bohr-Orbital Model

•Niels Bohr went to work with Rutherford in 1912 to solve the problem with his model:

Bohr suggested that the electrons in an atom orbit the positively-charged nucleus, in a similar way to planets orbiting the Sun

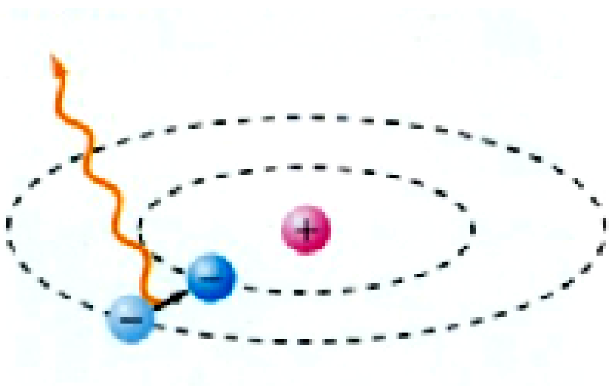
(but centripetal force provided by electrostatic attraction rather that gravitation)

Hydrogen atom: single electron orbiting positive nucleus of charge +Ze, where Z =1:

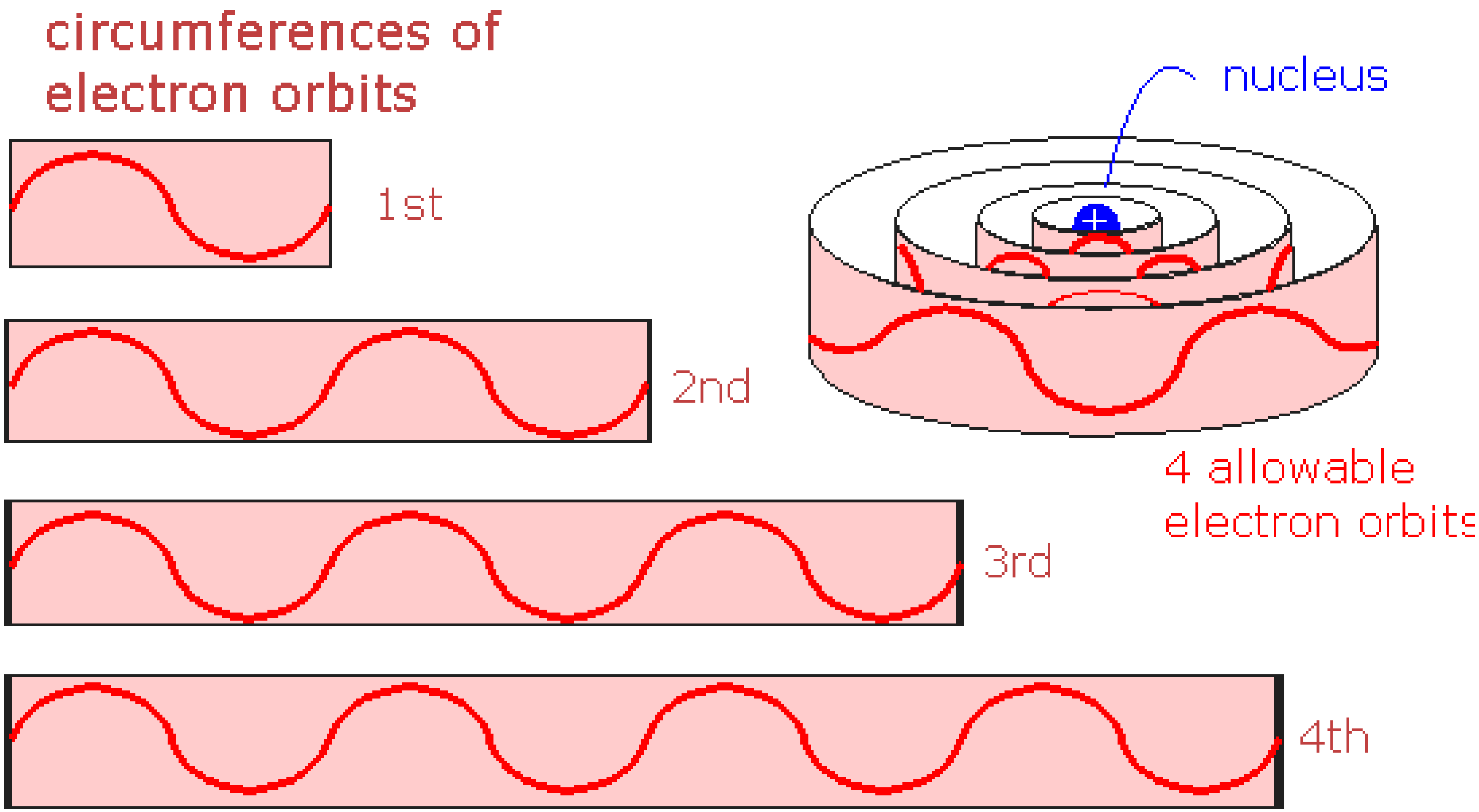


Bohr was able to show that only certain electron orbits are allowed.

That is, he applied the quantum idea to the orbits and concluded that an orbit could only exist if its circumference is some whole number multiple of the de Broglie matter wave ($\lambda = h / m v$) associated with the electron.



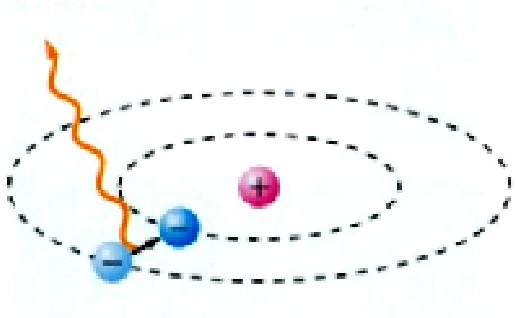
Now think back to de Broglie. He said that matter has an associated wave. In fact, you calculated some waves associated with moving electrons. Using de Broglie's idea, Bohr came up with an ingenious proposal. He said that the only electron orbits allowed would be those for which the electron wave would fit exactly on the circumference of the orbit. You can see from the picture below that the smallest allowed orbit has a circumference of $2\pi r_1 = \lambda$; the next largest allowed orbits have circumferences of $2\pi r_2 = 2\lambda$; $2\pi r_3 = 3\lambda$ and so on, up to the 4th orbit with a circumference of $2\pi r_4 = 4\lambda$.



Bohr Radius Equation

Bohr developed an equation to determine the radius of orbit of an electron:

$$r_n = (5.3 \times 10^{-11}\ \text{m})\ n^2$$



As you can see a Bohr radius is directly proportional to the square of the quantum number associated with the radius at that particular orbit where by:

where: n is the quantum number (ie. orbital level number) 1,2,3,etc.

5.29×10^{-11}m is the Bohr radius (when n=1 for hydrogen)

Example 1:

What is the orbital radius of an electron in a hydrogen atom in the third energy level?

Solution

Given n = 3

$r_n = ?$

Example 2:

If the orbital radius of an electron in a hydrogen atom is 2.12×10^{-10}m, at what energy level is the electron?

Example 3:

What distance does an electron travel when it drops from $n = 3$ to $n = 1$?

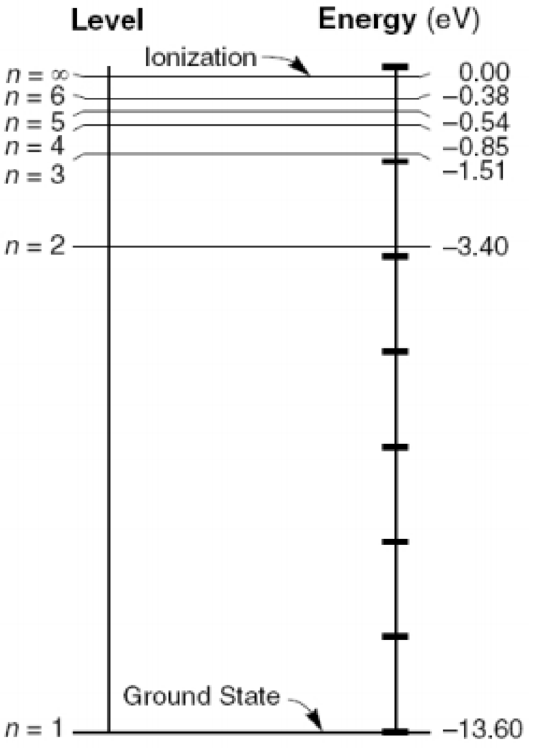
Equation for the total energy of an electron orbiting a nucleus

A derived expression for the energy of electrons at a certain level is:

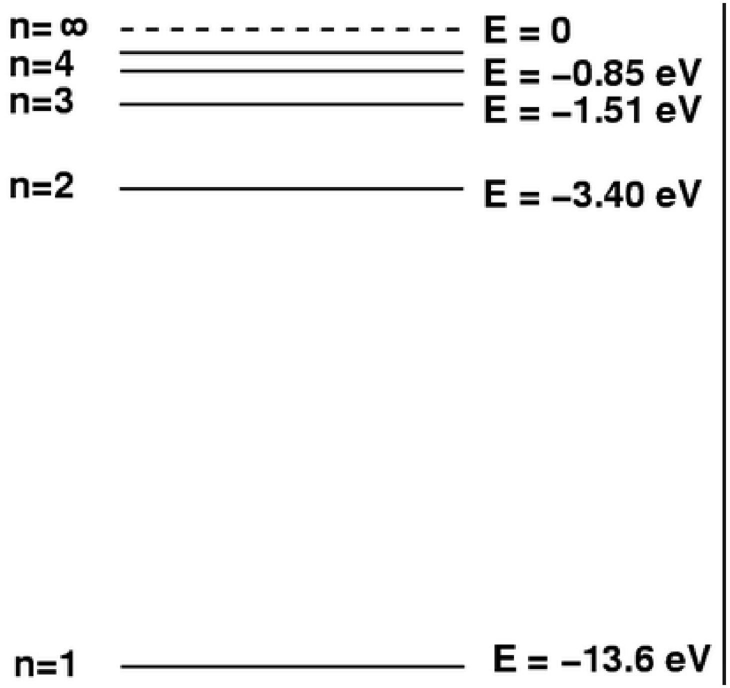
$$E_n = -\frac{2.18 x 10^{-18}}{n^2} J.$$

Finally, change 2.18 x 10^{-18} J to eV by dividing by 1.6 x 10^{-19} J/eV:

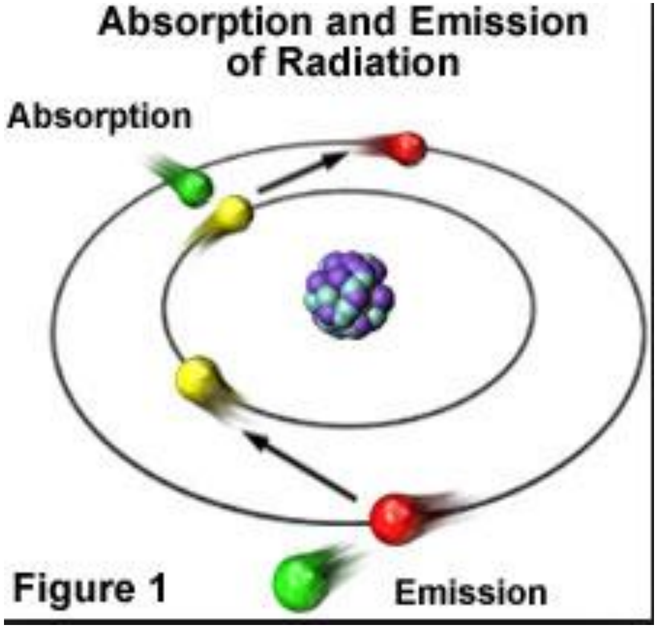
$$E_n = -\frac{13.6}{n^2} eV \quad \text{where } n = 1,\ 2,\ 3\ldots$$

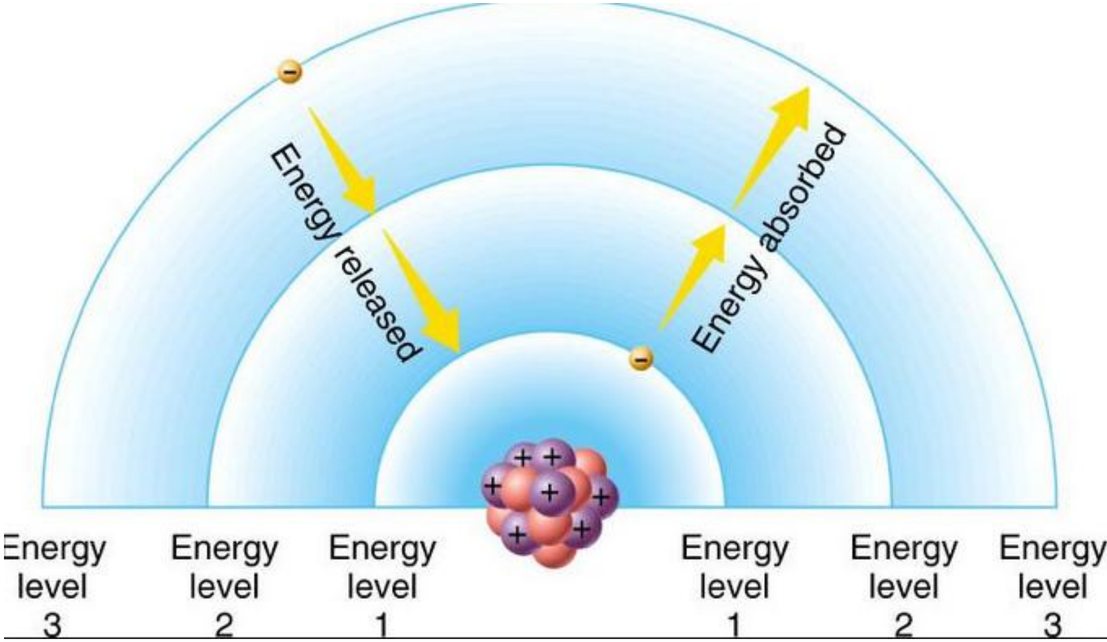


Why electrons don't lose energy and spiral into the nucleus.



Briefly! It can be explained with Bohr's model and the energy levels being negative. The electron has negative energy and can be viewed as being in an energy well. The electron would need to gain energy to escape from the well. Since it has less energy in the lower orbital levels, it must gain energy to jump to a higher orbital level (ie. further from the nucleus)

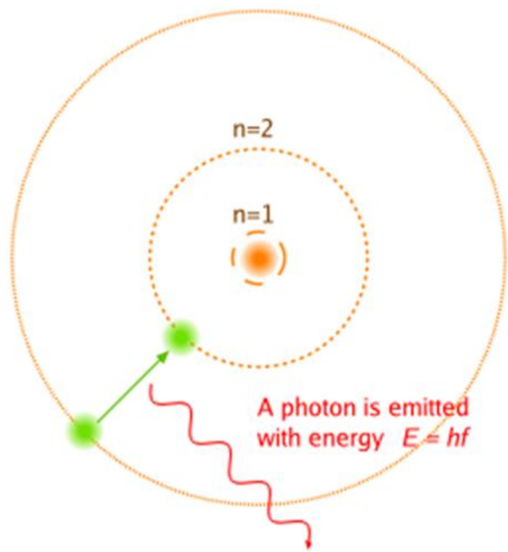




Absorption of Energy relates to the energy taken to raise an electron to a higher orbital level in that gas atom. The change in energy will have a negative value.

Emission Energy is determined by the given energy difference between orbital levels in that gas atom. It will be a positive value.

Photons are bundles of light energy that is emitted by electrons as they go from higher energy levels to lower levels.



Ground state: the lowest possible energy level an electron be at.

Excited state: an energy level higher than the ground state.

Ionization energy - the magnitude of energy needed to remove an electron completely from the nucleus (r = infinity). This energy is also equal in magnitude to that of the energy of the ground state (n = 0).

Bohr was able to use his new model to explain these spectral lines. His model, with various electron orbital levels, suggests that an electron emits energy (a photon) at **very specific energies when it drops from a higher energy level to a lower energy level.**

Determine the energy of the photon:

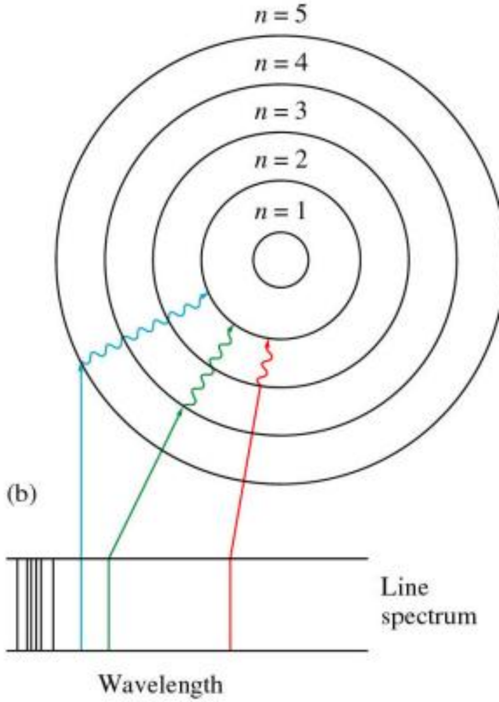
$$\Delta E e = E_u - E_L$$

ΔEe is the change in Energy (J or eV)

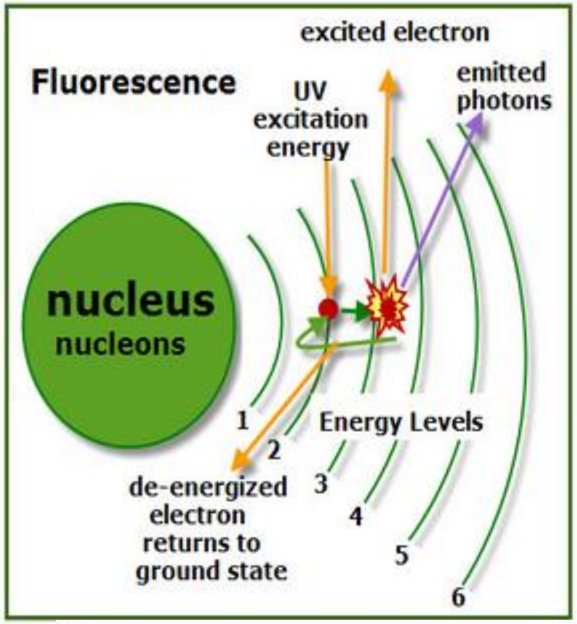
E_u is energy of upper quantum level *(J or eV)*

E_L is energy of lower quantum level *(J or eV)*

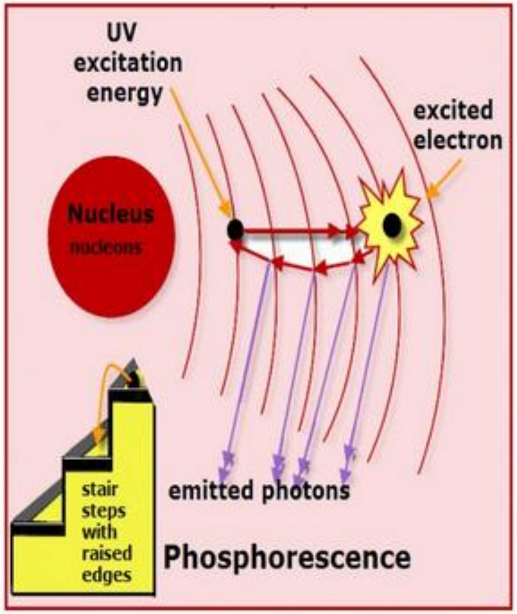
This effect suggests that energy at the atomic level is **quantized**



Bohr's Application of Quanta



Fluorescence : electrons absorbs photons and become excited and return to the original state, like a ball bouncing down steps The object emits visible light as long as there is a supply of excitation energy.

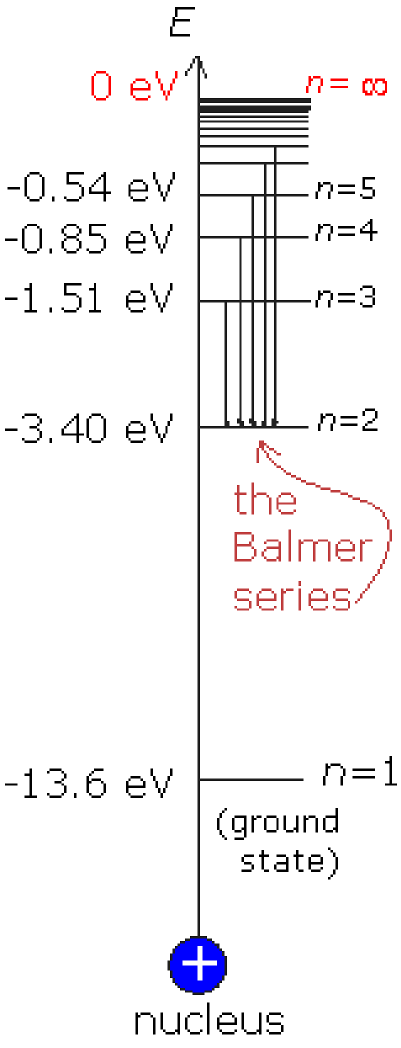


Phosphorescence when exposed to light, electrons of the material are excited to higher energies level and some become temporary stable. Some of the electrons stay in the stable state for seconds, hours or days before falling back. This is found in glow in the dark material such as tv remotes and key rings.

Example 1 Determining Energy of the Photon

In the picture a photon is emitted as an electron falls from the n=5 state to the n=2 state.

What is the energy of the photon?

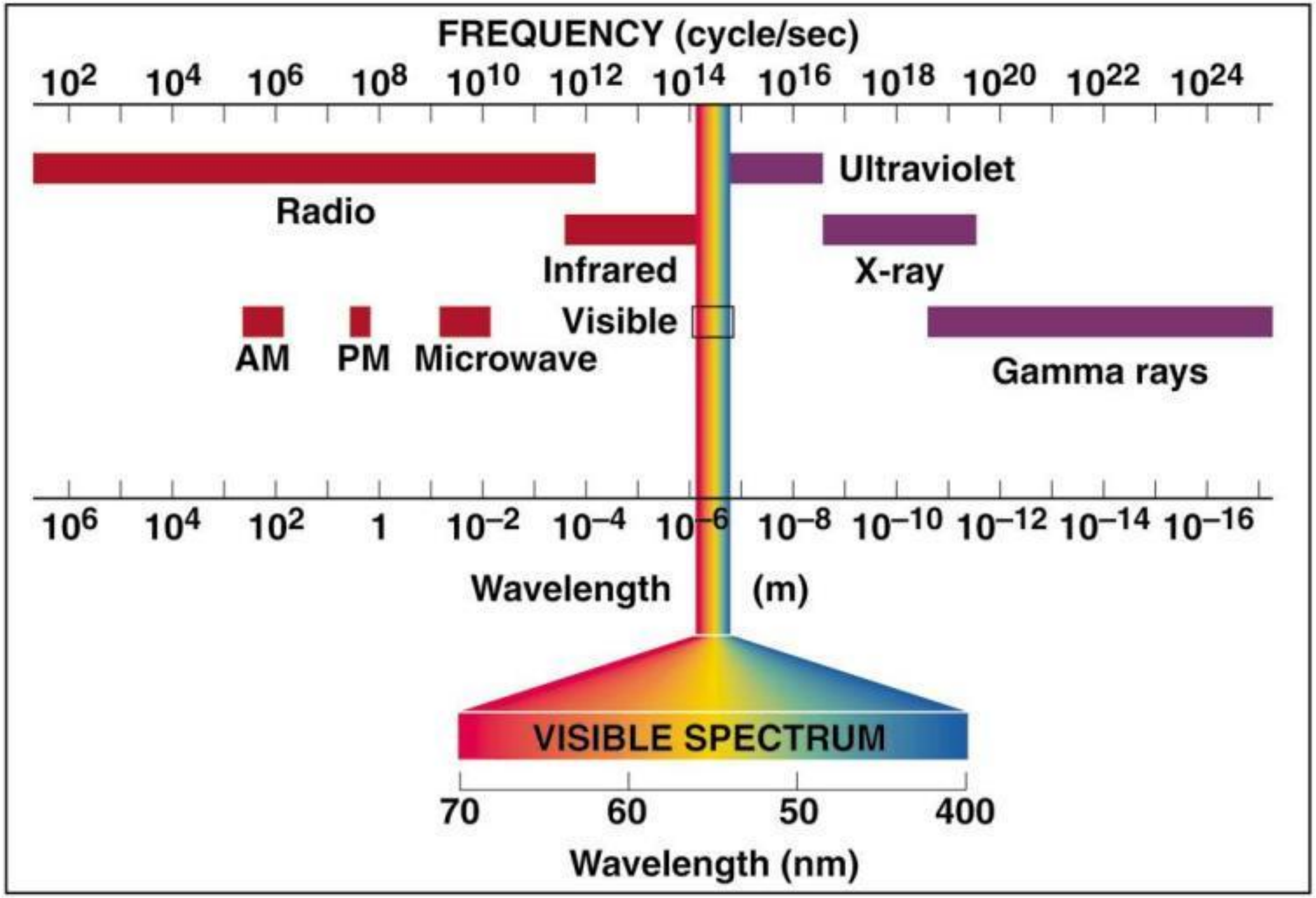


Example 2: Determine energy and Wavelength of Photon

An electron drops from the n=4 to the n= 1 energy level. In what region of the electromagnetic spectrum is this photon found?

Checking the wavelength:

$\lambda = 9.7 \times 10^{-8}$ m $= 0.97 \times 10^{-9}$ m = or about 1 nm. The photon is an x-ray

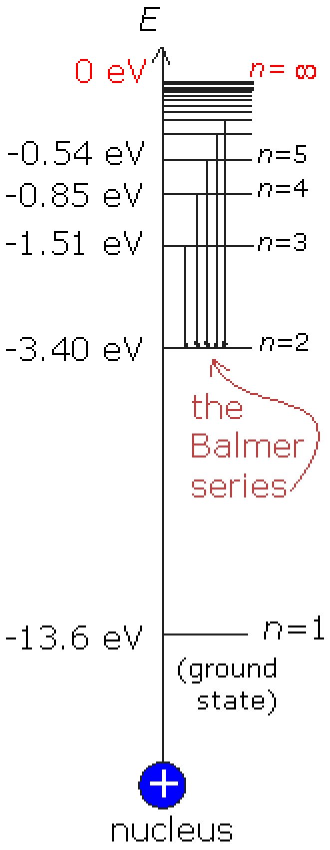


Also, read pg. 718 of text on The Wave- Particle Duality of Light and pay attention to Fig.17.24

Example 3: Ionization Energy

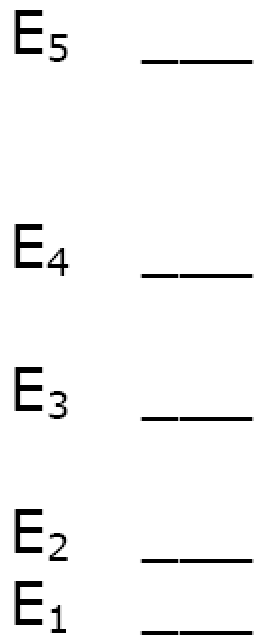
What is the ionization energy of hydrogen?

Basically, how much energy is required to strip the electron from a hydrogen atom so that only the positive nucleus remains. Assume that the electron is at n=1.

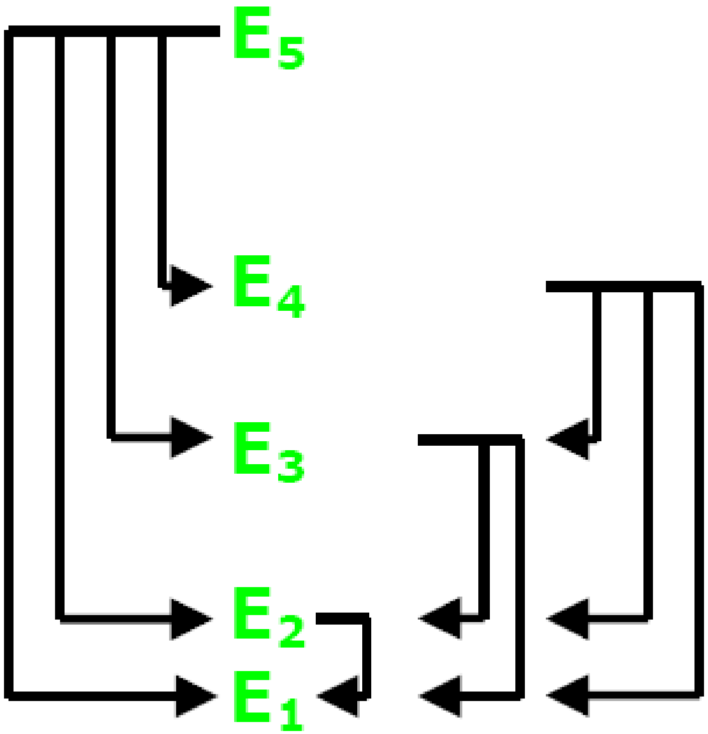


Example 4: Spectral Lines

How many different spectral lines can be produced by an atom with 5 energy levels?



Answer



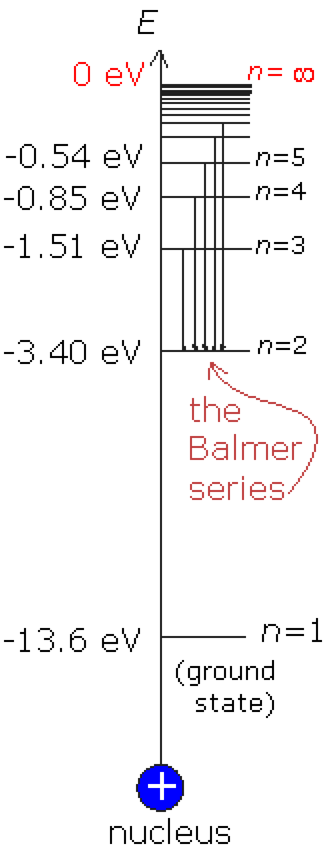
Summary

$r_n = (5.3 \times 10^{-11}\ \text{m})\ n^2$

the radius (rn) of the orbit as a function of the orbit number or quantum number, *n*

$$E_n = -\frac{13.6}{n^2} eV.$$

the energy (Ee) of the electron orbiting the nucleus as a function the nth orbital level



In dropping from the upper , to the lower , levels the electron loses energy Δ*E*e :

Δ*E*e = *E*u - *E*l

In your textbook:
on p. 731--do #13, #16
on p. 733--do #40-#45, #47
 (in #45 assume the drop is from infinity where $E = 0$.)

WORKSHEET ***Bohr's Application of Quanta***

Physics 3204

UNIT 3: Section 5

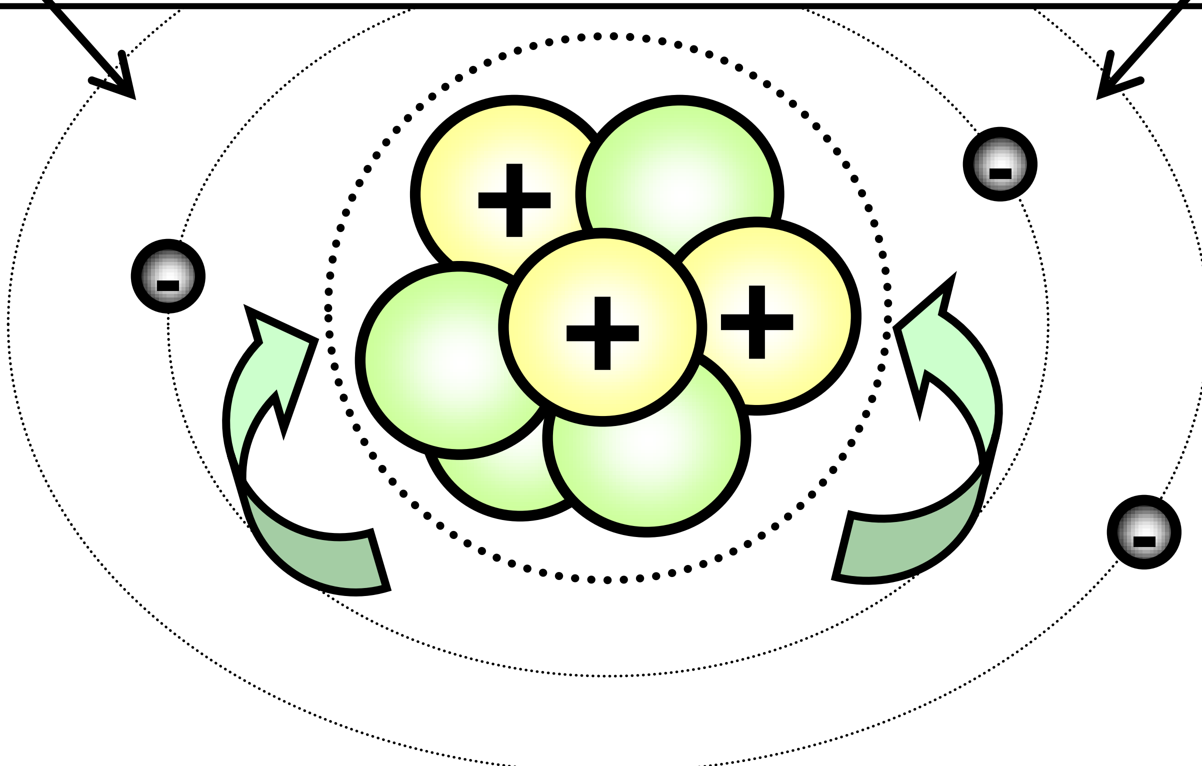
Nuclear Structure and Properties

Text Reference:
18.2 (pp. 741 – 743)

Revisiting Bohr's Model of the atom

- Protons and neutrons are grouped together to form the "center" or **nucleus** of an atom.

Notice that the electrons are not apart of the nucleus. Electrons orbit The nucleus in shells or energy levels



Only **protons** determine the type of substance. For example if the atoms each contain 79 protons (and 79 electrons), then you have gold.

Some important information about the atom

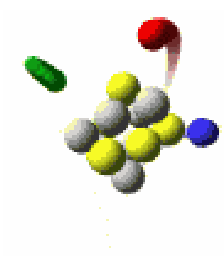
Nucleus - positively charged core of atom, which contains most of the mass.

Nucleons - particles which make up the nucleus, namely protons and neutrons.

Protons - particles with +1 charge and $m_p = 1.673 \times 10^{-27}$ kg

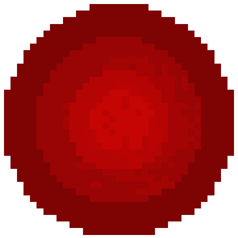
Neutrons - particles with no charge and $m_n = 1.675 \times 10^{-27}$ kg

Electrons - particles which orbit nucleus. They have -1 charge and $m_e = 9.11 \times 10^{-31}$ kg

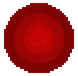


Atomic Number

- This refers to how many protons an atom of that element has.
- No two elements, have the same number of protons.



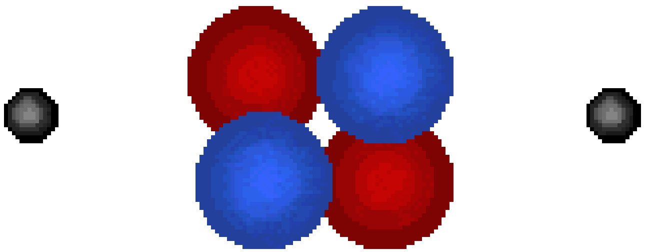
Bohr Model of Hydrogen Atom



Wave Model

Atomic Mass

- Atomic Mass refers to the “weight” of the atom.
- It is derived at by adding the number of protons with the number of neutrons.



This is a helium atom. Its atomic mass is 4 (protons plus neutrons).

What is its atomic number?

How do I find the number of protons, electrons, and neutrons in an element using the periodic table?

of PROTONS = ATOMIC NUMBER

# of ELECTRONS = ATOMIC NUMBER

# of NEUTRONS = ATOMIC WEIGHT _ ATOMIC NUMBER

ATOMIC FORMULA

4 Atomic mass — the number of protons and neutrons in an atom

He

2 Atomic number — the number of protons in an atom

number of electrons = number of protons

Isotopes

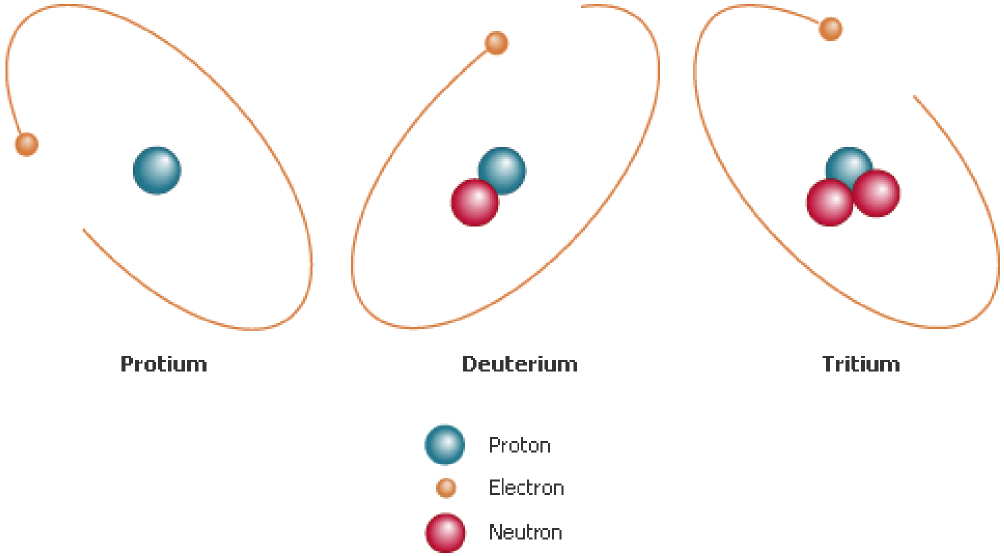
- **Isotopes** are atoms of the same elements that contain different numbers of neutrons. Neutrons carry no charge, they do not affect the chemical properties of the substance except to add weight.

Isotopes of chlorine

$^{35}_{17}Cl$ $^{37}_{17}Cl$

chlorine - 35 **chlorine - 37**

Three Isotopes of Hydrogen



Hydrogen isotopes: normal hydrogen - $^{1}_{1}H$ mass = 1.67353×10^{-27} kg

deuterium - $^{2}_{1}H$ mass = 3.34449×10^{-27} kg

tritium - $^{3}_{1}H$ mass = 5.00827×10^{-27} kg

Isotopes - atoms of the same element (same Z) but having differing numbers of neutrons and thus differing atomic mass (differing A).

Example 1

What is the atomic notation for the isotope of element X that has 30 electrons and 36 neutrons.

What element is this?

Example 2:

An atom has a mass number of 222 and an atomic number of 86. Find the name of the element, its symbol, the number of protons (or electrons), and the number of neutrons using a periodic table.

Example 3:

How many protons, neutrons, and nucleons are in the nucleus of:

$$^{45}_{20}Ca$$

Units For Mass of an atom

Three ways to write the mass of an atomic particle
In Table 18.1 on p. 742 of your textbook you will find three ways to write the mass of an atomic particle:

1. Kilogram

proton: 1.67 x 10-^{27} kg (actually 1.67262 x 10^{-27} kg)
neutron: 1.67 x 10-^{27} kg (actually 1.67493 x 10^{-27} kg)
electron: 9.11 x 10^{-31} kg (actually 9.1164 x 10^{-31} kg)

These are given in your text on page p. 566

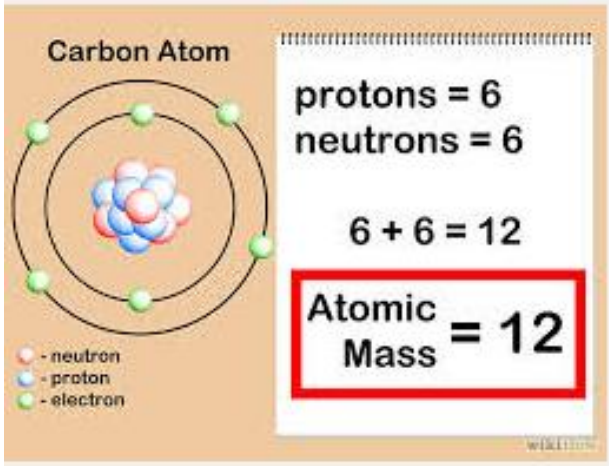
2. Unified atomic mass unit (amu), represented by the letter u.

As a result of the masses of atoms and subatomic particles being so small it was convenient to use atomic mass unit:

One atomic mass unit (1u) is equal to one twelfth of the mass of the most abundant form of the carbon atom—Carbon 12

1 u = 1.6605×10^{-27} kg.

An atom that is twice as massive as carbon-12 will have a mass of 24 u. Of course when considering isotopes the periodic table gives the mass of carbon as 12.011 u.



3. The electron-volt energy unit (energy equivalence unit)

We can use $E = mc^2$ to determine the energy equivalent (in electron-volts) of a particle with mass 1u.

$c = 2.9979 \times 10^{8}$ m/s
1 u = 1.6605×10^{-27} kg.

$E = mc^2 = 1.6605 \times 10^{-27}\ \text{kg} \times (2.9979 \times 10^{8}\ \text{m/s})^2$
$= 1.4924 \times 10^{-10}$ J.

Recall that 1 eV = 1.6022×10^{-19} J.

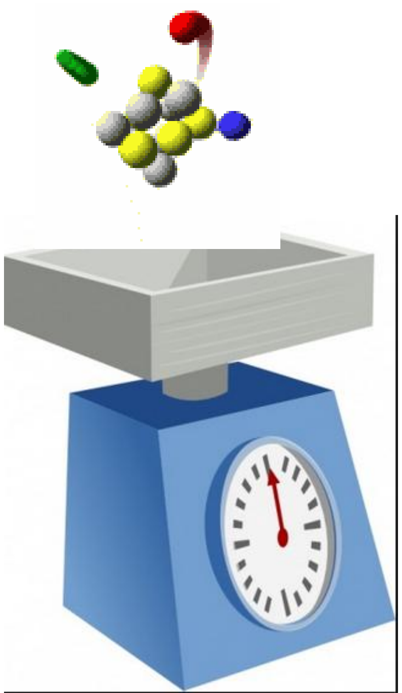
$E = 1.4924 \times 10^{-10}\ \text{J} \div 1.6022 \times 10^{-19}\ \text{J/eV}$
$E = 931{,}500{,}000\ \text{eV} = 931.5 \times 10^{6}\ \text{eV}$
$E = 931.5$ MeV (where M stands for 10^{6} or mega)

Summary

To convert between the units :

$1\ u = 1.6605 \times 10^{-27}\ kg = 931.5\ MeV/c^2$.

This conversions factor is found on your formula sheet



Try these on your own

Ex 1 - If an element has atomic mass of 18.9984 u, what is its mass in kg.

Answer: 3.1547×10^{-26} kg

Ex 2 – An element has a mass of 6.647×10^{-27} kg. What is its mass in unified atomic mass units (u) ?

Answer: 4.003 u

Ex 3 – A particle has a mass of 106 MeV/c^2.

What is this mass in atomic mass units (u) and in kg?

Answer 0.114 u or 1.89×10^{-28}

Ex 4 – What is the rest mass of a fluorine atom in MeV/c^2 and in kg?

Rest mass = 18.998403

= 17697 MeV/c^2

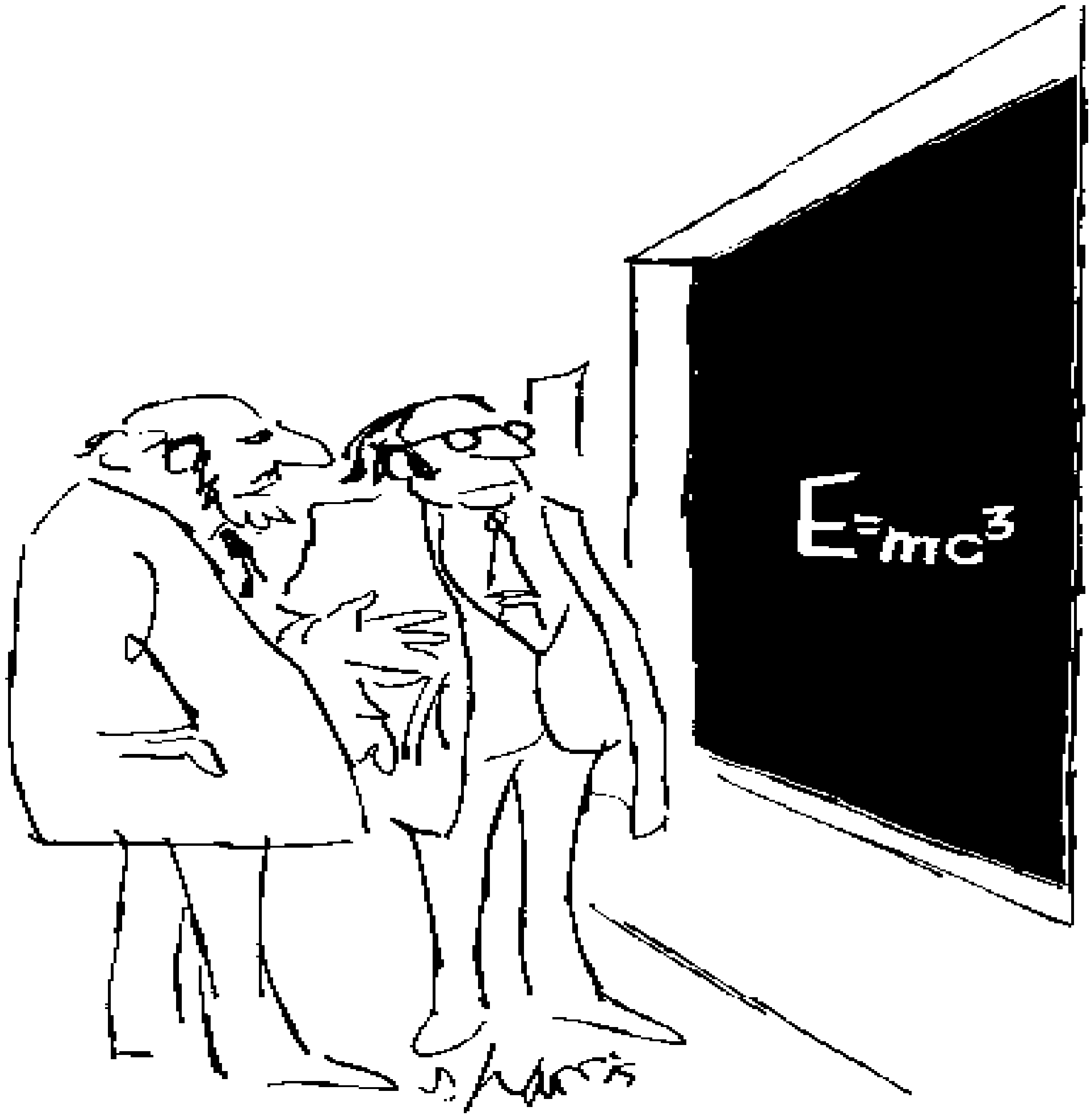
= 3.1547×10^{-26} kg

Physics 3204

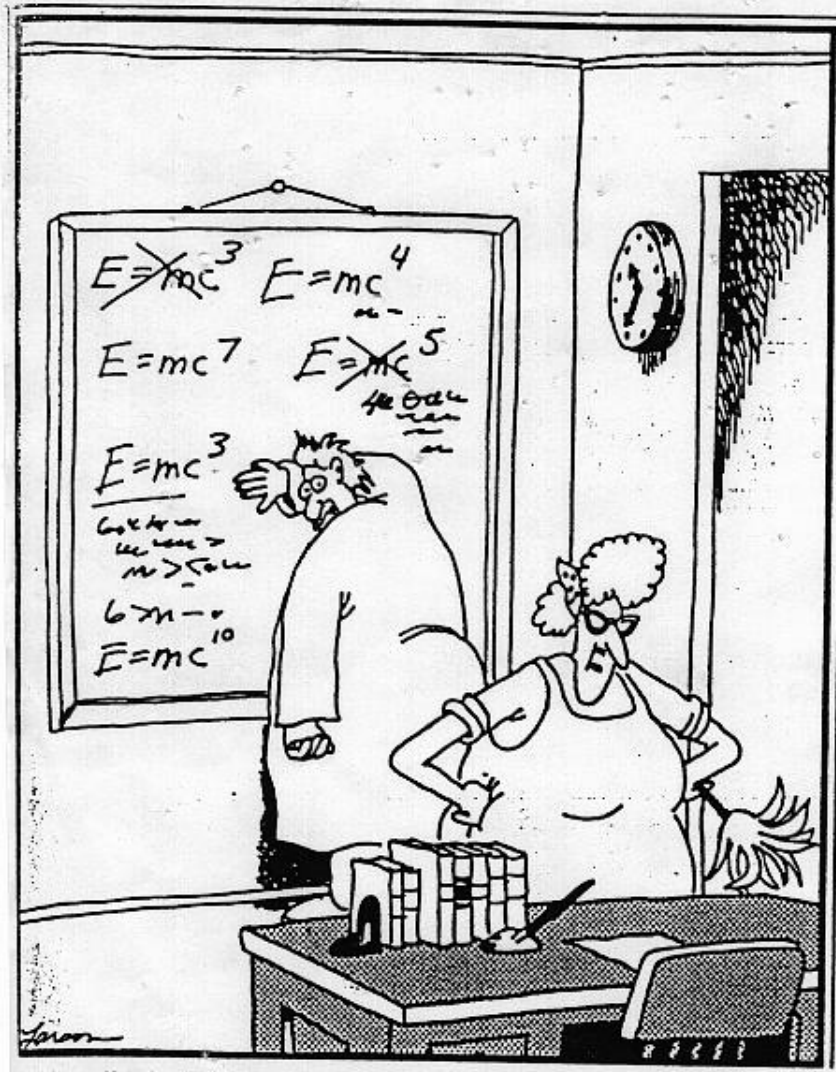
UNIT 3: Section 6

Mass Defect and Mass Difference

Text Reference:
18.2 (pp. 741 – 743)

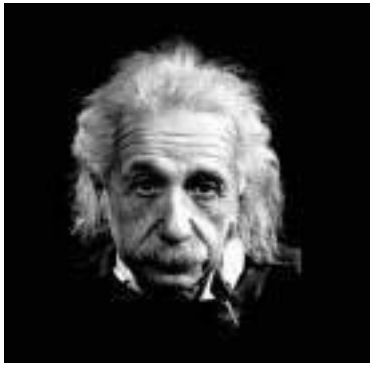


“These days *everything* is higher.”



"*Now* that desk looks better. Everything's squared away, yessir, squaaaaaared away."

$E = mc^2$: The Equivalence of Matter and Energy



Einstein's most famous contribution is the about the equivalence of matter and energy — **that a loss or gain in mass can also be considered a loss or gain in energy.**

$$E = m \cdot c^2$$

E = the energy equivalent to the mass (in joules),

m = mass difference (in kilograms), and

c = the speed of light in a vacuum (in meters per second).

Don't make plans for the end of the sun

The sun radiates power at 3.92×10^{26} Watts. So, in one second, it radiates 3.92×10^{26} Joules of energy. This translates into the sun losing about *4.36 billion kilograms of mass per second* — whoa! That's about 4.79 million tons of matter lost every second. You can almost hear solar scientists going nuts. Surely, at that rate, there will be no more sun left in a few weeks. They cry out, "Our mortgages! We'll have to get new jobs when the sun goes out!" What they shouldn't forget is that the sun has a mass of 1.99×10^{30} kg. Even at 4.36×10^{9} kg of mass lost per second, it will still last for a while. How long? If radiating away mass were the only physical mechanism at work, the sun would last $1.99 \times 10^{30} / 4.36 \times 10^{9} = 4.56 \times 10^{20}$ seconds. That's about 1.44×10^{13} years, or 144 billion centuries.

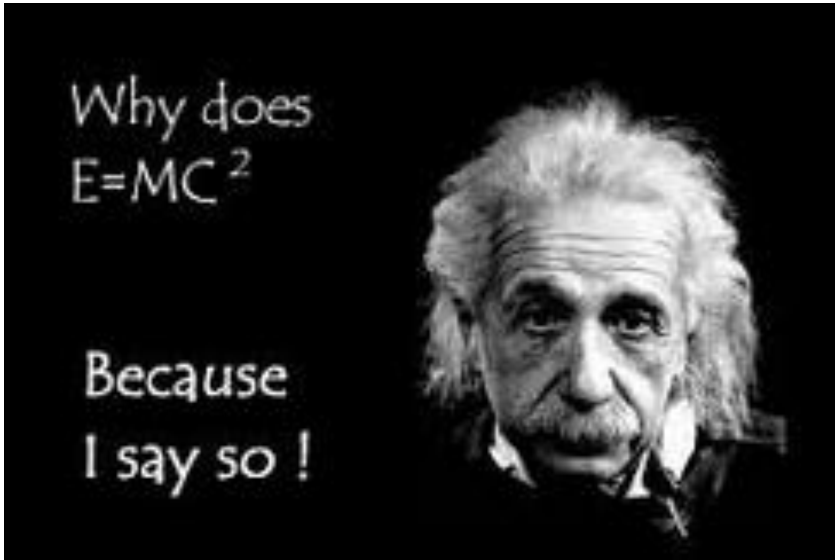
A huge amount of energy from a small amount of mass. Every process that releases energy is accompanied by an equivalent loss of mass. Every process that absorbs energy results in a gain of mass. The mass changes accompanying chemical reactions are too small to measure but mass changes due to nuclear reactions can be measured using a mass spectrometer. The following process releases energy (how do you know?):

The mass-energy equivalency formula can be used to calculate:

1) Binding Energy

2) Energy of a Fission Reaction

3) Energy of a Fussion Reaction



1. Binding Energy

The binding energy represents the amount of energy that must be supplied to break the nucleus into its individual protons and neutrons. (Conversely, it is the energy released when the nucleus is formed from individual protons and neutrons.)

The following process releases energy (how do you know?):

protons + neutrons $\rightarrow$ nucleus

Thus, the mass of a nucleus is less than the sum of the masses of the protons and neutrons from which it is composed! The difference in mass is called the **mass defect (m):**

Example 1: Binding Enegy

If the mass of a carbon-14 $^{14}_{6}C$ nucleus is 2.3252×10^{-26} kg, what is the binding energy of the carbon nucleus?

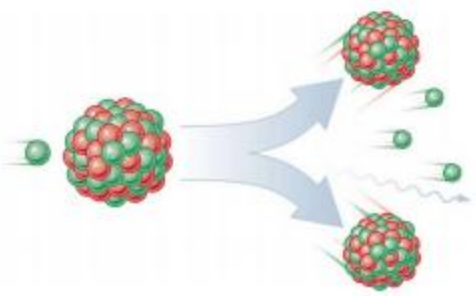
2) Fission Reaction

Fission = the splitting of a heavy nucleus into two nuclei with smaller mass numbers. This process is induced by absorption of a neutron by the reactant nucleus, and results in the release of energy and an additional 2 or 3 neutrons as products. For example 3 of the many possible outcomes of uranium-235 fission are:

$${}_{0}^{1}n + {}_{92}^{235}U \rightarrow {}_{38}^{90}Sr + {}_{54}^{143}Xe + 3\,{}_{0}^{1}n$$

$${}_{0}^{1}n + {}_{92}^{235}U \rightarrow {}_{52}^{137}Te + {}_{40}^{97}Zr + 2\,{}_{0}^{1}n$$

$${}_{0}^{1}n + {}_{92}^{235}U \rightarrow {}_{56}^{142}Ba + {}_{36}^{91}Kr + 3\,{}_{0}^{1}n$$



Example 2: Fission Reaction

Calculate the energy released in the reaction shown below.

$$^{6}_{3}\mathrm{Li} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{3}_{1}\mathrm{H}$$

Particle	Mass (u)
$^{6}_{3}Li$	6.01513
$^{1}_{0}n$	1.00867
$^{4}_{2}He$	4.0026
$^{3}_{1}H$	3.01604

Method 1:   Using Kilograms

Method 2: Using electron-volt energy units

3) Fusion Reaction

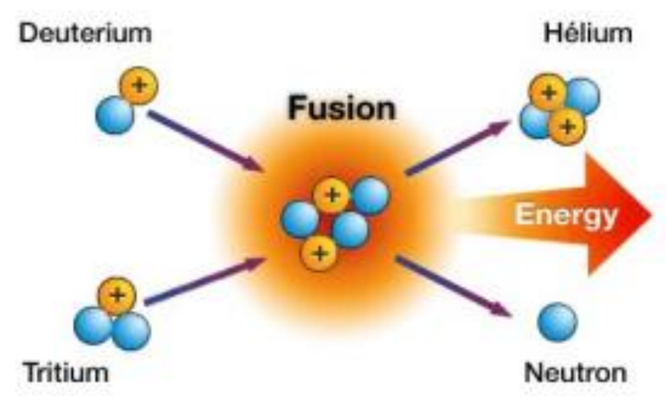
Fusion the combining of two light nuclei to form a heavier, more stable nucleus. For example, the following reactions (among others) take place in the sun:

$$^1_1H + ^1_1H \rightarrow ^2_1H + ^0_1e$$

$$^1_1H + ^2_1H \rightarrow ^3_2He$$

$$^3_2He + ^1_1H \rightarrow ^4_2He + ^0_1e$$

$$^3_2He + ^3_2He \rightarrow ^4_2He + 2^1_1H$$



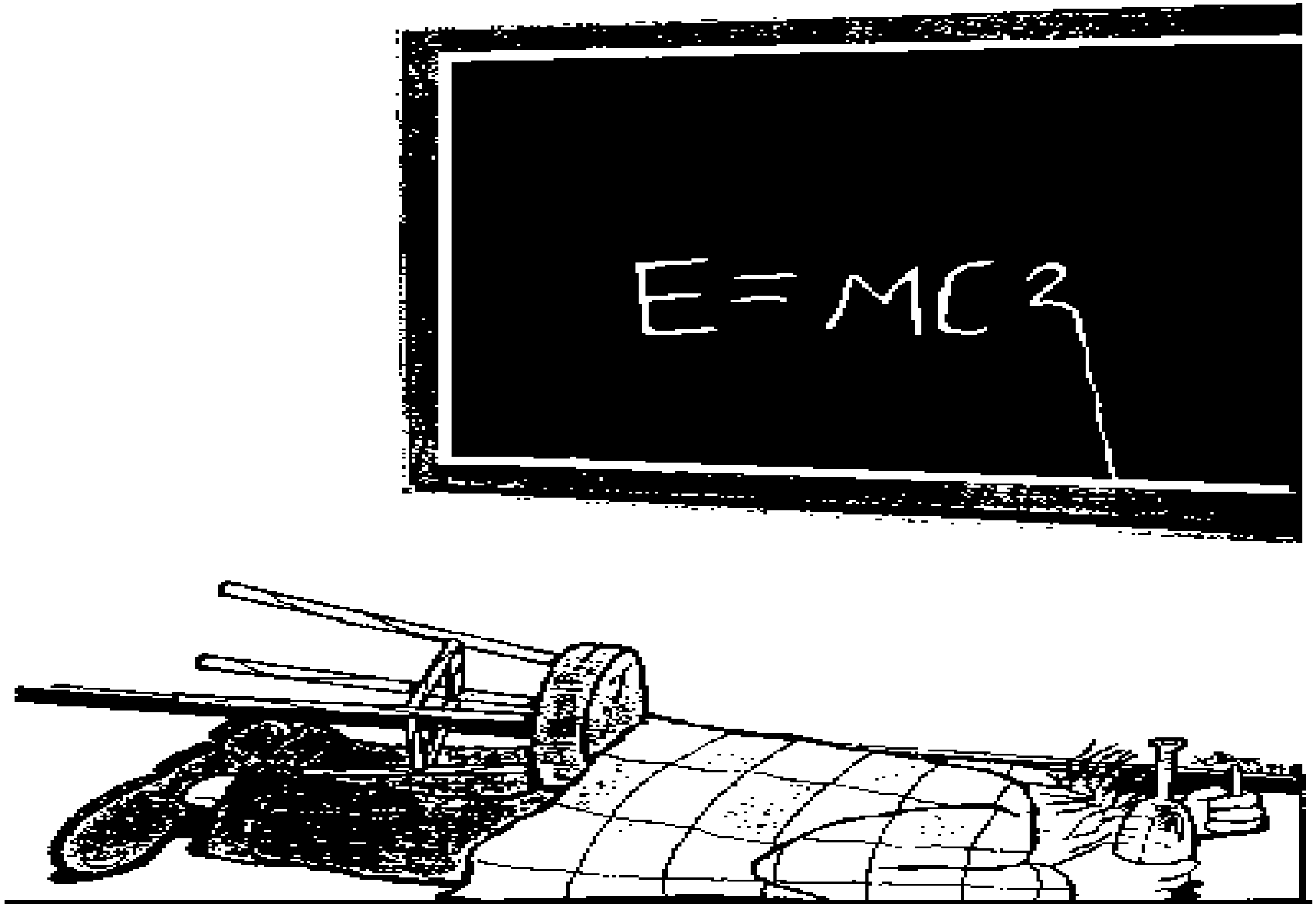
Because of the large binding energies involved in a nucleus, both fission and fusion involve energy changes of more than a million times larger than those energy changes associated with chemical reactions.

Example 3: Fusion Reaction

Calculate the energy produced in the reaction below.
June 2007

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n + \text{energy}$$

Particle	Mass (Kg)
$^{2}_{1}H$	3.3444 x 10^{-27}
$^{3}_{1}H$	5.0082 x 10^{-27}
$^{4}_{2}He$	6.6463 x 10^{-27}
$^{1}_{0}n$	1.6749 x 10^{-27}



Early in his carrer, Einstein discovered
the hazards of drinking and deriving.

In your textbook:

on p. 743--do #1-#4
on p. 772--do #2-#6
on p. 773--do #36-#42 (#38 and #39 are based on material in the popup link at the end of page b under the "Lesson" button. Use 1 u = 931.5 MeV/c2)

Movie = $E = mc^2$

Physics 3204

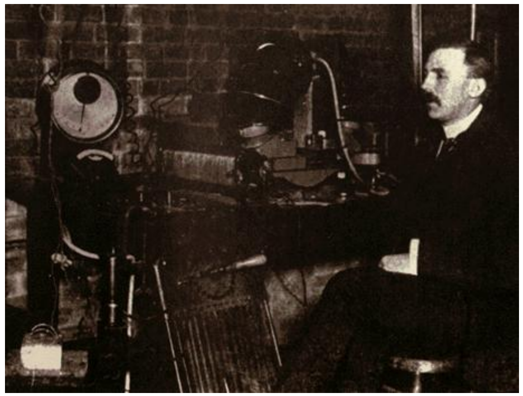
UNIT 3: Section 7

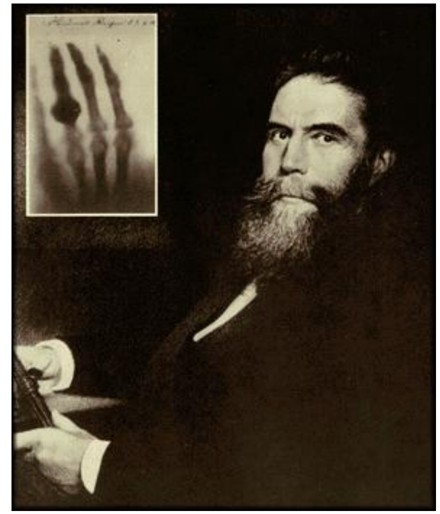
Natural Transmutations and Radioactive Decay

Early Pioneers in Radioactivity

Rutherford:

Discoverer Alpha and Beta rays 1897



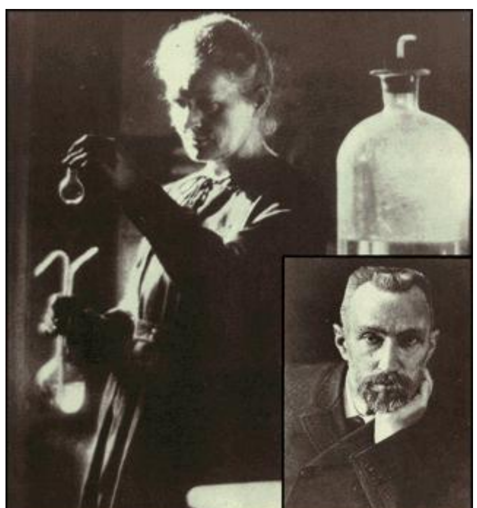


Roentgen:

Discoverer of X-rays 1895

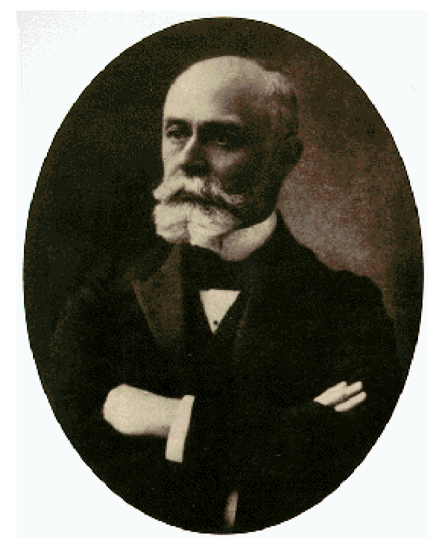
The Curies:

Discoverers of Radium and Polonium 1900-1908



Becquerel:

Discoverer of Radioactivity 1896



In physics 2204 you learned that there are **four basic forces in nature:**

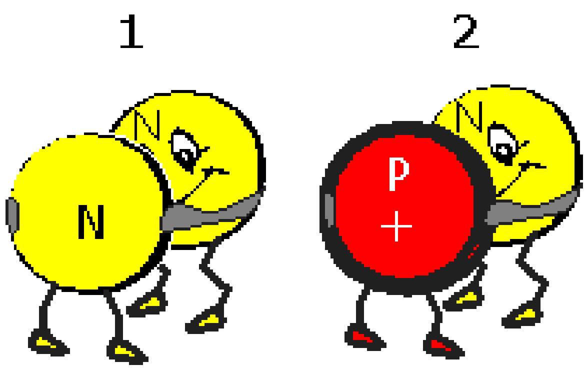
🖫 the gravitational force
🖫 the electromagnetic (electric) force
🖫 the strong nuclear force
🖫 the weak nuclear force

Here we will look closer at the **electric force** (which is included in the electromagnetic force) and the **strong nuclear force** (within the nucleus)**.**

Nuclear Stability

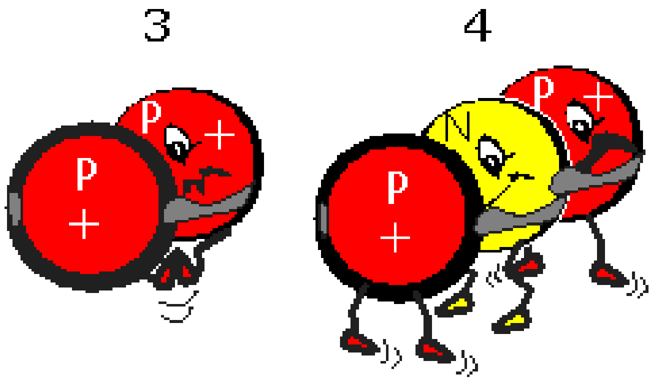
- The 4-part picture below may help you understand the roles of these two forces.

- The yellow particles are neutrons and the **red particles are protons**.



1 - Here you see **two neutrons attracted to each** other. Their arms represent the **strong nuclear force**. Obviously, the strong nuclear force is <u>not</u> caused by charge because neutrons have no charge.

2 - The **same strong nuclear force exists between protons and neutrons**.



3 - Here there is a conflict:

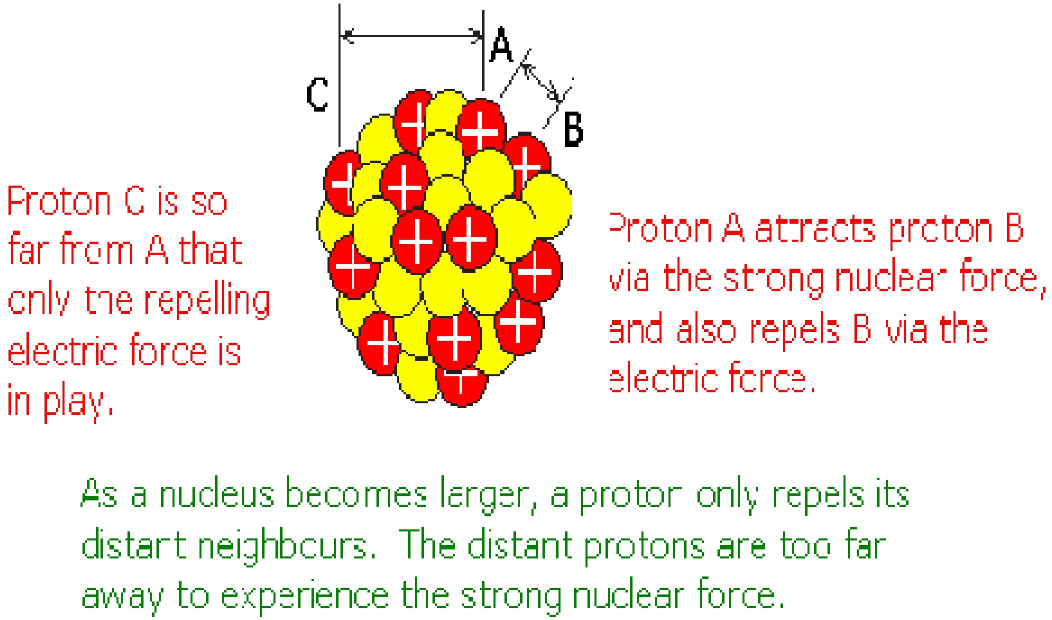
- The **protons are bound together by the strong nuclear force**.

- However, all protons have the same positive charge, and you know from earlier lessons that "like charges repel". **These two protons are being repelled by the electric force.**

- If a nucleus were made up entirely of protons, it would be in great danger of disintegrating because the repelling electric force would overcome the strong nuclear force.

4 - The Neutron has placed himself between the two protons. All three particles are bound together by "the glue" of the **strong nuclear force**, and the protons are separated a little bit so the repelling electric force has a smaller effect.

- However, **as *Z* or atomic number increases**, the electric repelling force among the many protons would cause the nucleus to disintegrate to some degree if it were not for many more neutrons than protons.



- **H**owever, when a nucleus becomes large (Z > 82), **the short-range strong nuclear force that acts only between neighboring particles cannot counterbalance the repelling electric force that each proton exerts on all other protons.**

RADIOACTIVITY

You should not get the idea that an unstable nucleus suddenly goes "sproing", with pieces going in all directions. Usually **a limited number of particles, or a limited amount of energy is emitted from the nucleus. This is referred to as**

Radioactivity refers to the spontaneous disintegration of nuclei to form new nuclei and a release of energy.

- That is, particles or energy might be **emitted from a parent nucleus** resulting in a **new element called a daughter nucleus** which itself might be unstable and subsequently emit more particles or energy.

WHAT IS RADIOACTIVITY

- Is the spontaneous breakdown of an unstable nucleus.
- Results in the emission of particles or electromagnetic radiation.
- It is found naturally and in artificially produced sources.
- Radioactivity cannot be detected by human senses.
- All naturally occurring elements with atomic numbers greater than 83 are radioactive, as well as some isotopes of lighter elements.

Applications of radioactivity

- Many satellites use radioactive decay from isotopes with long half-lives for power because energy can be produced for a long time without refueling.

- Isotopes with a short half-life give off lots of energy in a short time and are useful in medical imaging, but can be extremely dangerous.

- The isotope carbon-14 is used by archeologists to determine age.

Transmutation

Transmutation refers to the changing of one element into another by the process of radioactivity

A transmutation entails a change in the structure of atomic nuclei and hence may be induced by a nuclear reaction, such as neutron capture, or occur spontaneously by radioactive decay, such as alpha decay and beta decay

A radioactive substance changes into another substance because particles are emitted from its nucleus, we say that the original parent element is decaying.

NATURAL	ARTIFICIAL
The element undergoes spontaneous decay because it is unstable. These reactions occur "spontaneously" (on its own) We start with ONE element on the RIGHT side of the arrow and end up with TWO things on the product side (right side)	For this change to happen, high-energy particles are fired at the element. In this reaction, two things are being combined: **(1) The nucleus being bombarded** **(2) The high-energy particle** We start with TWO things on the left side of the arrow and 2 or more things on the right side of the arrow

TRY THESE

$$^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}e$$ Natural

$$^{87}_{37}Rb \rightarrow ^{0}_{-1}e + ^{87}_{38}Sr$$ Natural

$$^{227}_{92}U \rightarrow ^{223}_{90}Th + ^{4}_{2}He$$ Natural

$$^{27}_{13}Al + ^{4}_{2}He \rightarrow ^{30}_{15}P + ^{1}_{0}n$$ Artificial

$$^{11}_{6}C \rightarrow ^{0}_{+1}e + ^{11}_{5}B$$ Natural

$$^{238}_{92}U + ^{1}_{0}n \rightarrow ^{239}_{94}Pu + 2\,^{0}_{-1}e$$ Artificial

$$^{239}_{94}Pu + ^{1}_{0}n \rightarrow ^{147}_{56}Ba + ^{90}_{38}Sr + 3\,^{1}_{0}n$$ Artificial

1)Natural Transmutations: Alpha Decay

- Occurs when the nucleus is too large.
- An alpha particle is emitted, reducing the size of the nucleus.

Alpha particles consist of **2 protons and 2 neutrons**. This accounts for its mass and its charge. The atomic notation for an alpha particle is:

$^{4}_{2}\alpha$ ···· has the same form as $^{4}_{2}He$. You must remember, however, that the alpha particle has no electrons. Consequently, alpha particles must be **helium nuclei**

- Example:

$$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He.$$

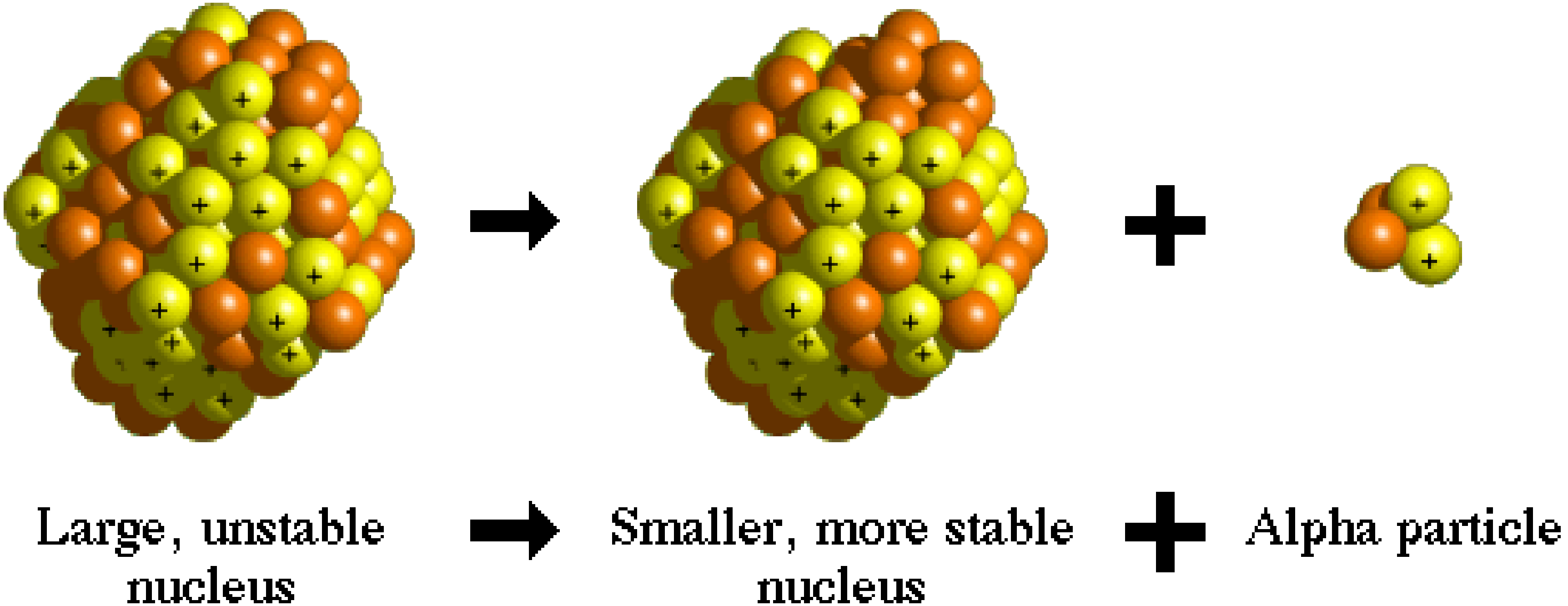
1)Natural Transmutations: Alpha Decay

Alpha particles consist of **2 protons and 2 neutrons**. This accounts for its mass and its charge. The atomic notation for an alpha particle is:

$^{4}_{2}\alpha$ …. has the same form as $^{4}_{2}He$. You must remember, however, that the alpha particle has no electrons. Consequently, alpha particles must be **helium nuclei**

Beta particles have mass and charge exactly equal to that of an **electron.** In other words, beta particles are electrons. They are usually designated with a negative sign like this: β-

Alpha Decay



http://education.jlab.org/glossary/alphadecay.gif

3.6.3 – Natural Transmutations: Writing Equations for Decay

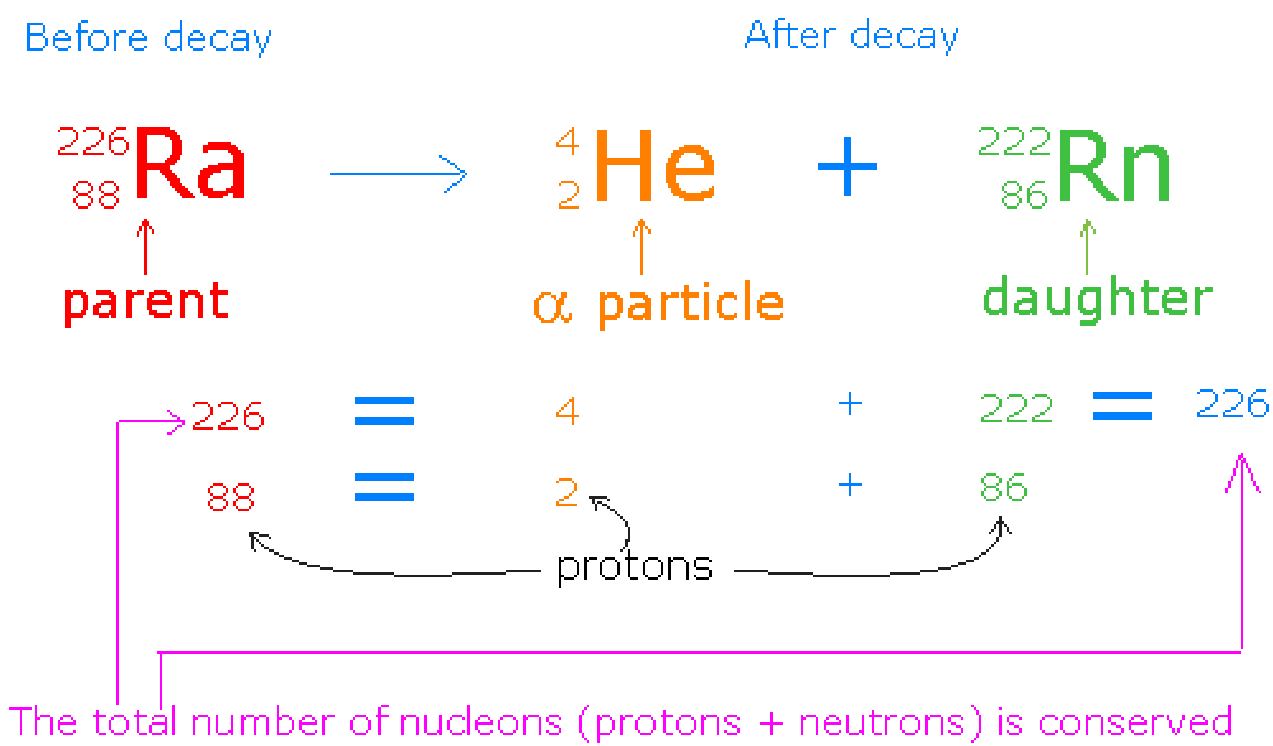
Alpha Decay

- If

- In the case of **alpha decay**, an α particle, or $^{4}_{2}He$, is emitted from the parent nucleus.

- Suppose the parent substance is $^{226}_{88}X$. If you look up Z = 88 in the periodic table, you will see that X is **radium**. So, the parent element is . $^{226}_{88}Ra$

Radium experiences Alpha Decay into Radon

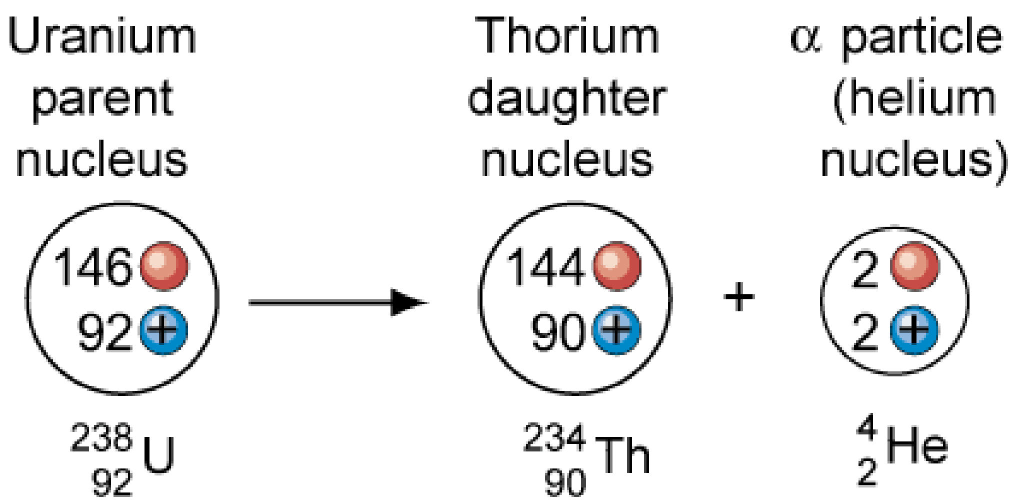


The general notation for alpha decay is therefore:

Parent Element		Daughter Element		α Particle
$^{A}_{Z}X$	$\rightarrow$	$^{A-4}_{Z-2}Y$	$+$	$^{4}_{2}He$

$$^{A}_{Z}X \rightarrow \, ^{A-4}_{Z-2}Y + \, ^{4}_{2}He$$

Example: Alpha Decay of Uranium



Remember the general notation for alpha decay is :

Parent Element		**Daughter Element**		**α Particle**
$^{A}_{Z}X$	$\rightarrow$	$^{A-4}_{Z-2}Y$	$+$	$^{4}_{2}He$

$$^{A}_{Z}X \rightarrow ^{A-4}_{Z-2}Y + ^{4}_{2}He$$

Ex 2 - An unstable polonium atom, $^{218}_{84}Po$,spontaneously emits an alpha particle

and transmutes into a daughter element (Y).

Determine the *A* and *Z* numbers of the new element and refer to the periodic table to identify the new element. Write an equation to show the nuclear process.

$$^{218}_{84}Po \rightarrow ^{A}_{Z}Y + ^{4}_{2}He$$

The atomic mass numbers, A, must be conserved. So: 218 = A + 4

A = 218 – 4 = **214**

The atomic numbers, Z, must be conserved.
So: 84 = Z + 2

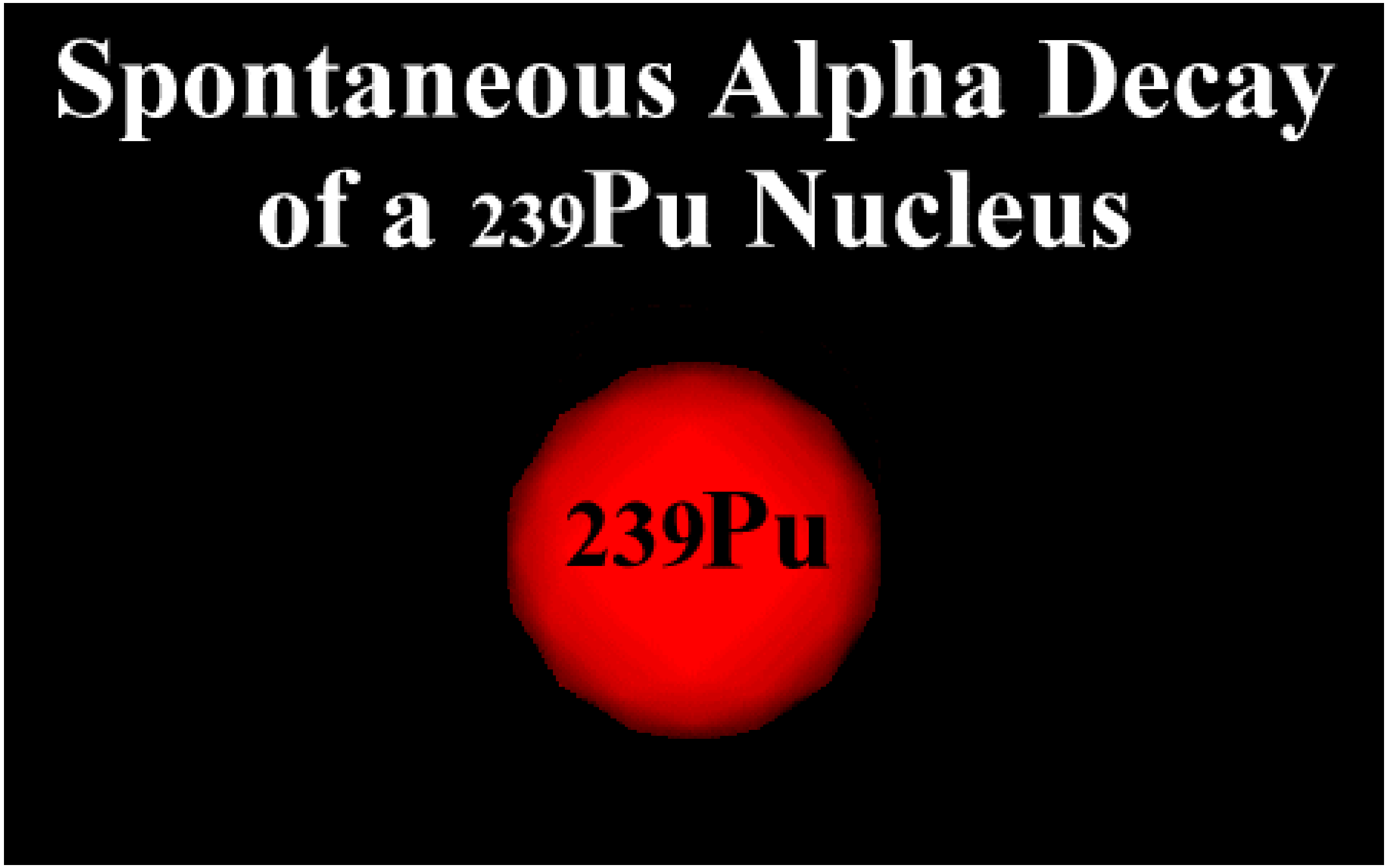
Z = 84 – 2 = **82**

From the periodic table, this is **Lead**, symbol **Pb**.

So, Daughter Element is $^{214}_{82}Pb$

Alpha decay equation

$$^{218}_{84}Po \rightarrow ^{214}_{82}Pb + ^{4}_{2}He$$



There is a difference in mass between the original nucleus and the sum of the mass of the alpha particle and resulting nucleus. This lost mass is converted into energy using the formula $E = mc^2$; the energy would equal the kinetic energy of the particle and the recoil energy of the resulting nucleus.

Summary Alpha particles

- are positively charged particles emitted from alpha decay
- these particles are helium nuclei
- are slightly deflected in an electric or magnetic field
- are emitted at high speeds
- have the lowest penetration power - up to 5 cm in air
- can be stopped by a thin layer of paper or aluminum
- results in the original nucleus changing - atomic mass decreases by four and atomic number decreases by two

2)Natural Transmutations: Beta Decay

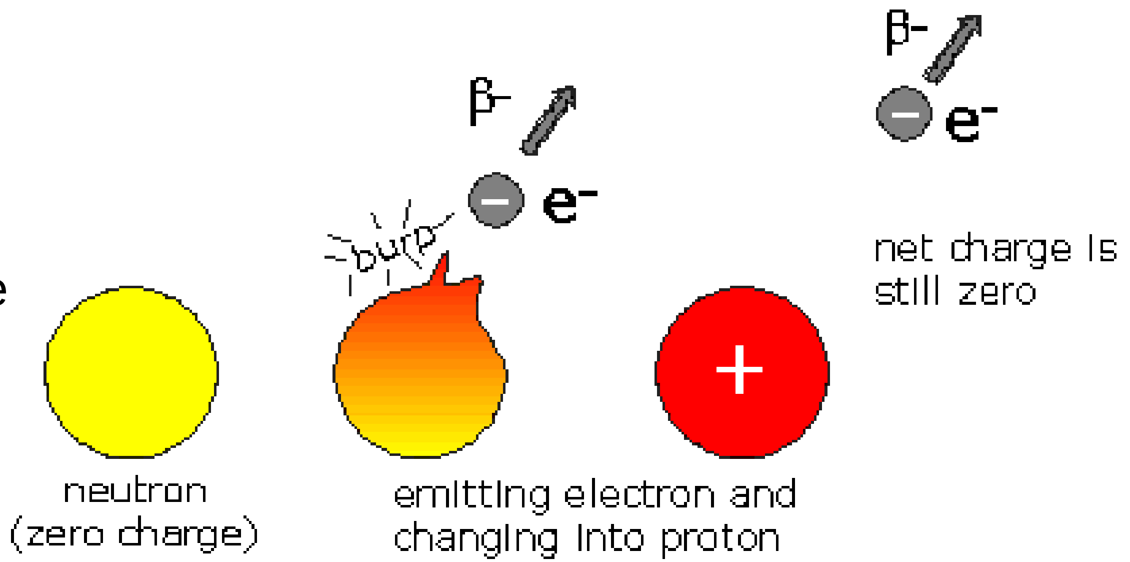
Occurs because the nucleus has too many neutrons relative to protons

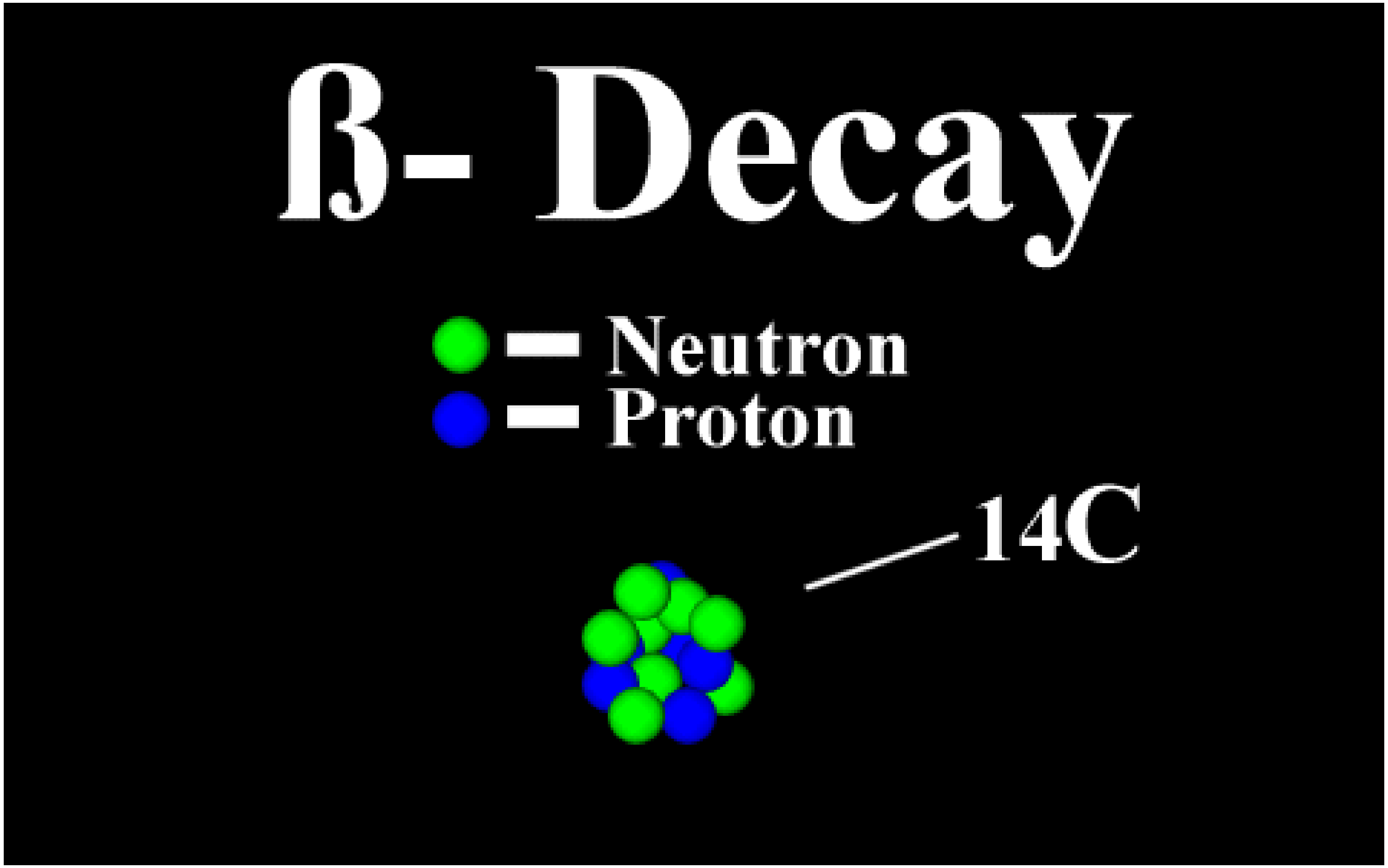
There are two types of Types of Beta decay:

Type 1: β - decay (electron emission)

The parent nucleus emits an electron (e-) as a neutron decays to a proton

- The picture shows a neutron changing into a proton, emitting an electron as it does so. Note that the amount of charge is conserved. It was zero before the decay, and adds up to zero after the decay



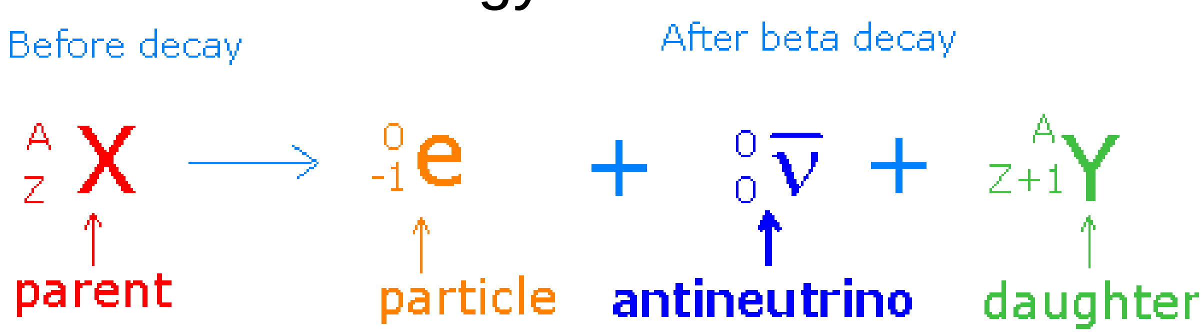

ß- Decay
Neutron
Proton
14C

- Researchers discovered that the emitted electron did not have as much energy as it should for energy to be conserved.

- It was concluded that there must be another particle emitted along with the electron to account for the missing energy.   The missing particle was said to have zero mass (or very nearly zero) and zero charge! It was given the name **neutrino**.

- If fact, it was necessary that the particle accompanying the β- decay be an antineutrino and not a neutrino. The symbol for neutrino is 🖫 and the symbol for antineutrino is $\bar{\upsilon}$.

- The process of Beta✐ Decay is summarized in the following equation. It includes the production of the antineutrino needed to balance the energy before and after.



- For the antineutrino, Z is also zero because it has no charge.

- However, for the emitted electron which has one unit of negative charge, so $Z = -1$.

- If you like, you can simplify the β- decay equation by omitting the antineutrino term.

Parent Element		Daughter Element		β Particle
$^{A}_{Z}X$	$\rightarrow$	$^{A}_{Z+1}Y$	$+$	$^{0}_{-1}e$

- The number of particles (protons + neutrons) is A on the left-hand side, and $A + 0 = A$ on the right-hand side.

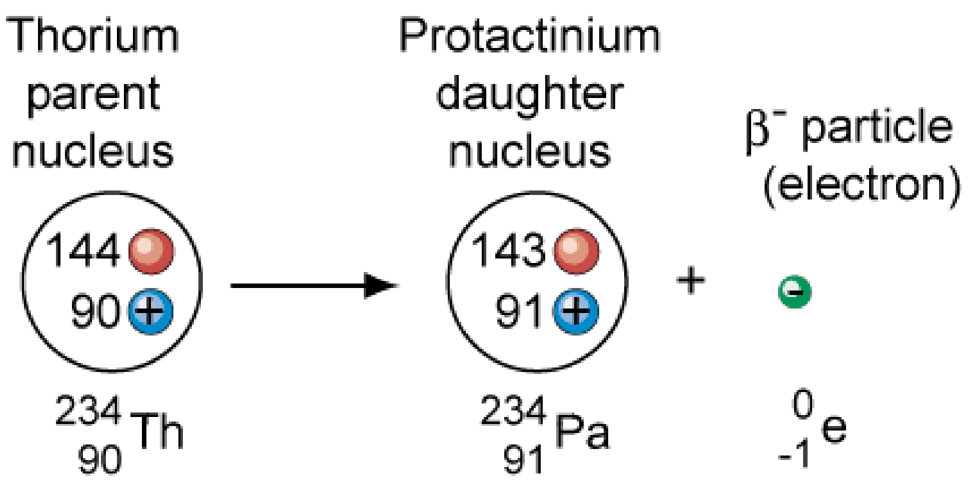
- The amount of charge is Z on the left-hand side and $Z + 1 + (-1) = Z$ on the right-hand side.

Example: Thorium Undergoes β- Decay

- One neutron converts to a proton and a β particle (electron) is released.

- Since we now have an extra proton in nucleus, **the atomic number, Z, of the daughter element goes up by 1.**

- The **atomic mass number, A, remains the same**: $^{234}_{90}\mathrm{Th} \rightarrow {}^{234}_{91}\mathrm{Pa}$



Ex - Carbon-14 has 6 protons (and therefore 8 neutrons) in its nucleus. One of the neutrons suffers β- decay and the carbon transmutes to a daughter nucleus. Write out this reaction in symbols and determine the name of the daughter element.

β✏ Decay of Carbon-14

Parent Element		**Daughter Element**		**β- Particle**
$^{14}_{6}\mathrm{C}$	$\rightarrow$	$^{A}_{Z+1}\mathrm{Y}$	$+$	$^{0}_{-1}\mathrm{e}$

- Since the β✏ particle has no mass, the atomic mass number, A, remains unaffected. So, for **daughter element A = 14**

- With β✏ decay, the **atomic number, Z, of the daughter element goes up by 1.** So the **daughter is atomic number 7.** This is **Nitrogen**, symbol **N**.

- The daughter element is

$$^{14}_{7}\mathrm{N}$$

β✏ Decay of Carbon-14 (antineutrino omitted)

$$^{14}_{6}\mathrm{C} \rightarrow \, ^{14}_{7}\mathrm{N} + \, ^{0}_{-1}\mathrm{e}$$

Type 2: β + Decay (positron emission)

occurs because a nucleus has too many protons relative to neutrons.

In β+ decay a <u>positron</u> (e+) is emitted as a proton decays into a neutron.

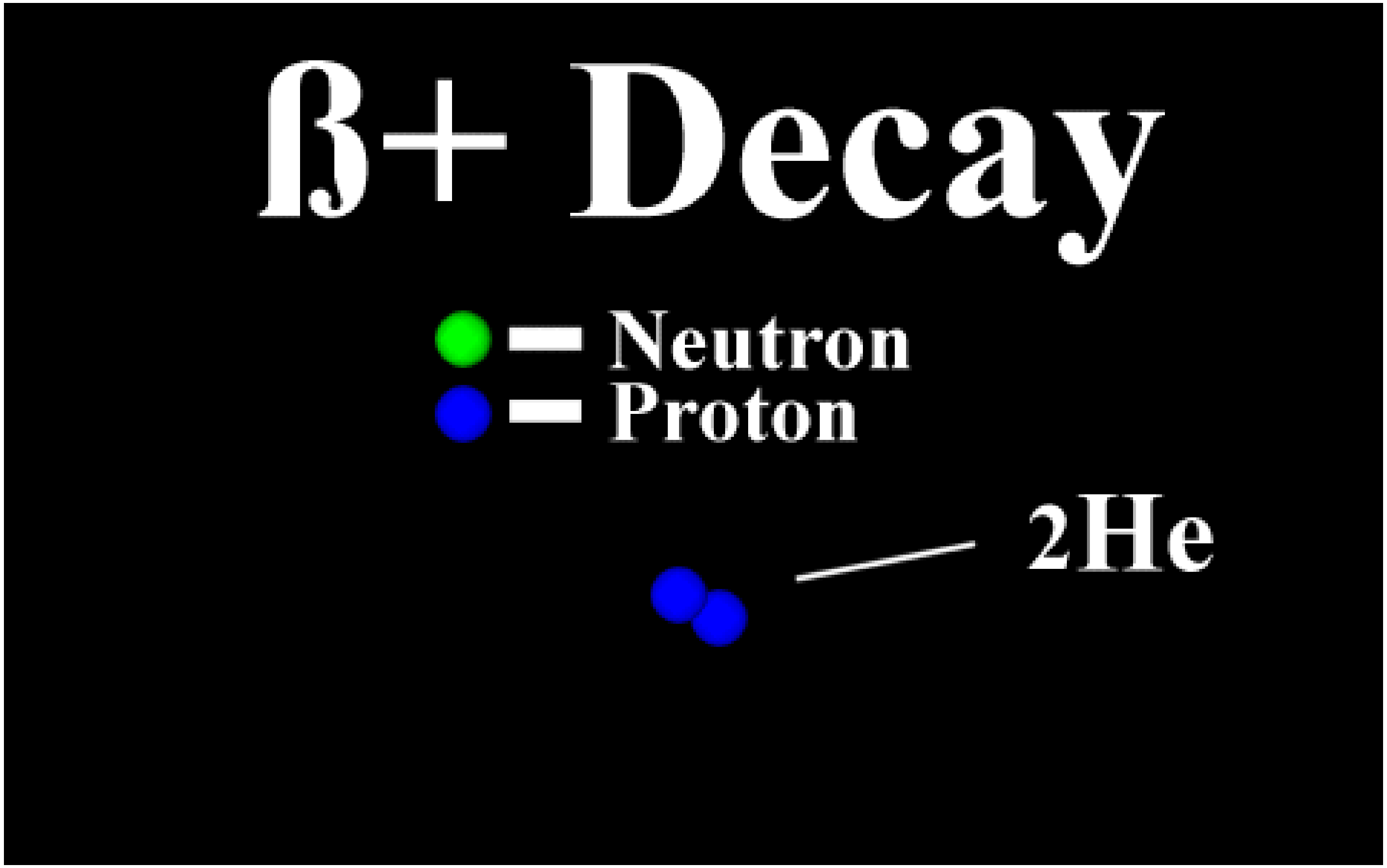
- Also, **we now have a <u>neutrino</u> accompanying the positron in order that energy be conserved.**

- In β- decay, the *Z* number of the daughter element increased by 1. **In β+ decay the *Z* number of the daughter element will decrease by 1.** The decrease occurs because a charged proton changes into an uncharged neutron.

Parent Element	Daughter Element	Positron	neutrino

$$^{A}_{Z}X \rightarrow \, ^{A}_{Z-1}Y + \, ^{0}_{1}e + \, ^{0}_{0}\upsilon$$

- For simplicity, the neutrino can be omitted from the β + Decay equation.



ß+ Decay
= Neutron
= Proton
2He

Ex - Sodium-22 has 11 protons (and therefore 11 neutrons) in its nucleus. One of the protons suffers β+ decay and the sodium transmutes to a daughter nucleus. Write out this reaction in symbols and determine the name of the daughter element.

β+ Decay of Sodium-22

Parent Element		Daughter Element		Positron		neutrino
$^{22}_{11}Na$	$\rightarrow$	$^{A}_{Z-1}Y$	+	$^{0}_{1}e$	+	$^{0}_{0}\upsilon$

$$^{22}_{11}Na \rightarrow \ ^{A}_{Z-1}Y + \ ^{0}_{1}e + \ ^{0}_{0}\upsilon$$

- Since the β✐ particle has no mass, the atomic mass number, A, remains unaffected. So, for **daughter element A = 14**

- With β+ decay, the **atomic number, Z, of the daughter element goes down by 1.** So the **daughter is atomic number 10.** This is **Neon**, symbol **Ne**.

- The daughter element is

$$^{22}_{10}Ne$$

β+ Decay of Sodium-22 (neutrino omitted)

$$^{22}_{11}Na \rightarrow \ ^{22}_{10}Ne + \ ^{0}_{1}e$$

Summary Beta particles

- are electrons that are emitted from beta decay
- are deflected greatly in an electric or magnetic field
- its direction of reflection is opposite to that of particles
- they travel at various speeds, sometimes approaching the speed of light
- medium penetration power - 10 m in air
- can penetrate several centimeters of aluminum
- results in the original nucleus changing - atomic mass remains the same and atomic number increases by one

3)Natural Transmutations: Gamma Decay

- Occurs when a nucleus has excess energy.

- The parent and daughter nuclides are the same.

- Example:

$$^{87}_{38}\text{Sr}^* \rightarrow {}^{87}_{38}\text{Sr} + \gamma\,.$$

The * in the reaction denotes an excited nuclear state.

When an **electron falls from a high energy level to a low energy level, a photon of electromagnetic energy is emitted.** Even though a gamma ray is a photon of electromagnetic energy it is not produced in that way.

- A γ ray is produced not because an excited electron falls to a lower level, but **because an excited nucleus decays to a lower level.**

Q. How can a nucleus be in an excited state?

A. - One way for it to be excited is **if it is a daughter nucleus that has just been transmuted from a parent nucleus.**

- We have already seen three ways that a daughter element can be produced: α decay, β- decay, and β+ decay.

- In these processes the daughter element was always on the right-hand side of the nuclear equation.

- If the daughter element is in an excited state, then a γ ray may also have to added to the right-hand side of all three equations.

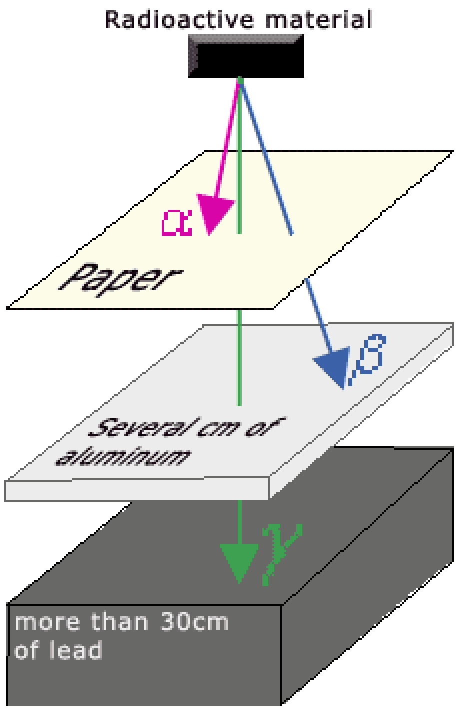
- Since a γ ray has no mass and no charge, it is just a matter of tacking it on. You don't have to worry about changing the *A* and *Z* numbers. For example, **a complete β- decay process including the emission of a gamma ray** looks like this:

Parent Element		Daughter Element		β Particle		Anti-neutrino		γ ray

$$^{A}_{Z}X \rightarrow \; ^{A}_{Z+1}Y + \; ^{0}_{-1}e + \bar{\nu} + \gamma$$

Summary: Gamma Rays

- are high energy electromagnetic radiation
- highest penetration power - 2 km in air
- can penetrate a minimum of 30 cm of lead
- the composition of the original nucleus does not change when these rays are emitted



Electron Capture and Gamma Decay

- There is another way to produce an excited daughter element. The process is called **electron capture.**

- As the phrase suggests, **in electron capture the parent nucleus absorbs an electron**. This means **one of the protons decays into a neutron.** (You can picture the electron "canceling" the positive charge of the proton).

- Because the parent nucleus absorbs an electron, for the first time you see two terms on the left-hand side of the nuclear equation. A general equation is given below:

$$ {}^{A}_{Z}X + {}^{0}_{-1}e \longrightarrow {}^{A}_{Z-1}Y + \bar{\nu} + \gamma $$

parent; captured electron; excited daughter; neutrino; gamma ray

- Concentrate on the right-hand side of the equation above. Realizing that the γ ray comes from the daughter nucleus, and omitting reference to the neutrino, a tidier expression is

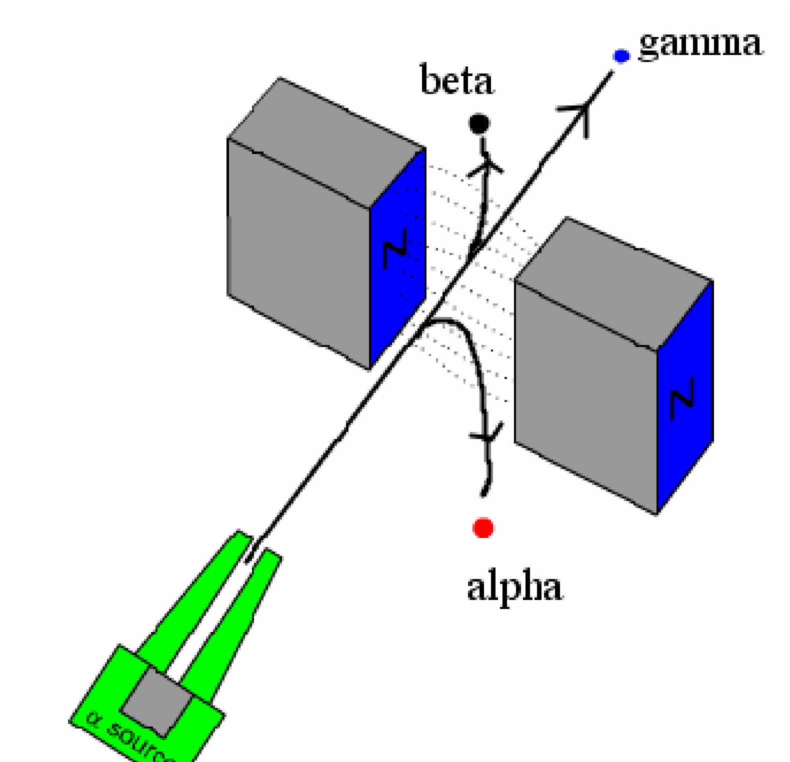
$$ {}^{A}_{Z-1}Y \rightarrow {}^{A}_{Z-1}Y + \gamma $$

- Because the γ ray has no mass and no charge, **there is no effect on the *A* and *Z* numbers from parent to excited daughter.**

Radioactive decay involves an unstable nucleus giving off a particle or ray, and in the process becoming a more stable nucleus.

There are several ways to detect what the particle/ray is.

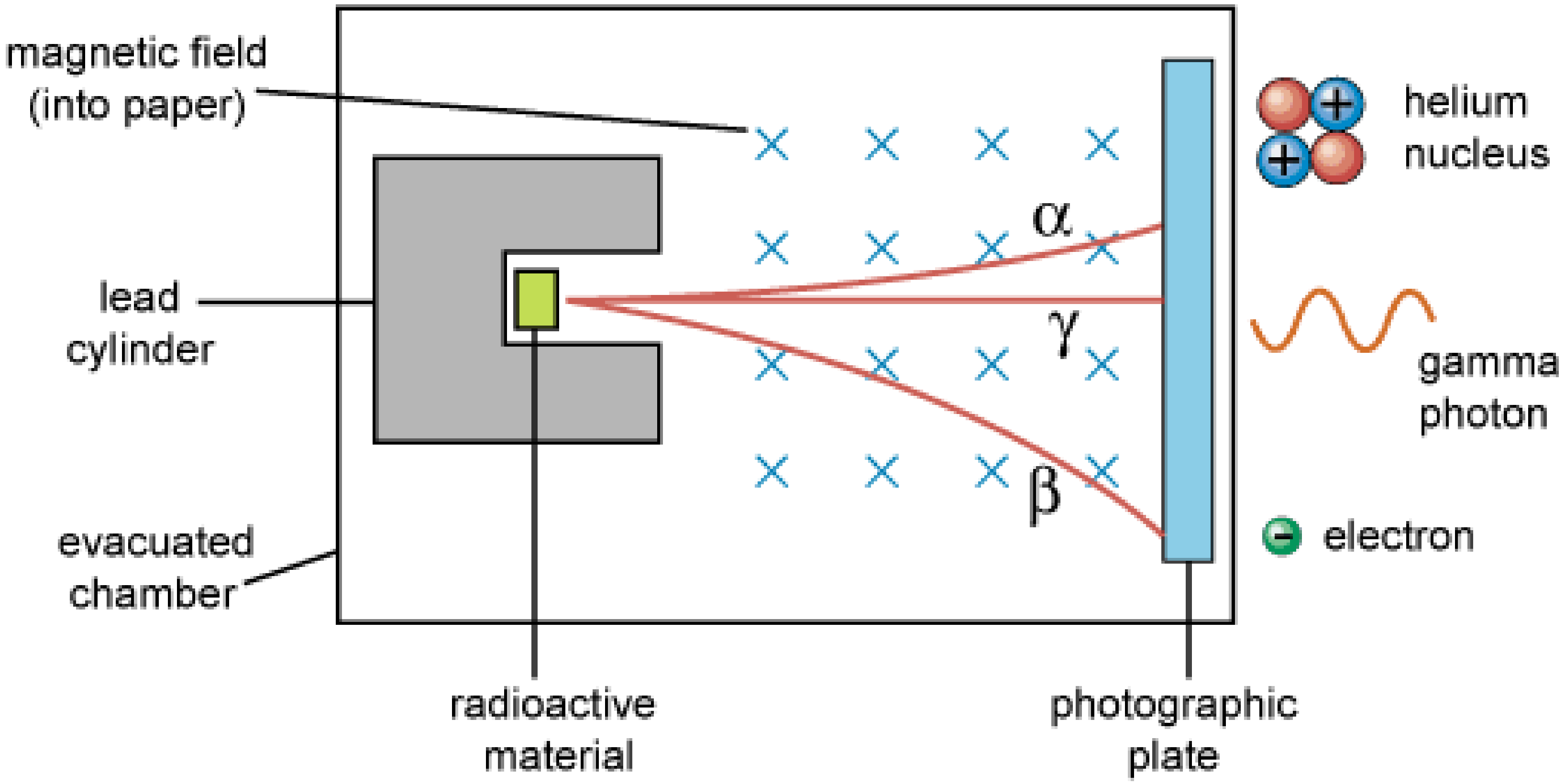
- The negative sign is important because, as time went on, another particle was discovered. **It has the same mass as an electron**, but the charge of a **proton!** That is, it has a positive charge. Such a particle is called a **positron**, and is designated by the symbol $\beta+$



- alpha and beta particles are bent in opposite directions

- whereas the gamma rays are not deflected

Magnetic Deflection of Particles – Side View



Alpha and Beta particles are bend in opposite directions (opposite charges on each) by a magnetic field, while gamma rays are not deflected (no charge).

How can these particles be seen?

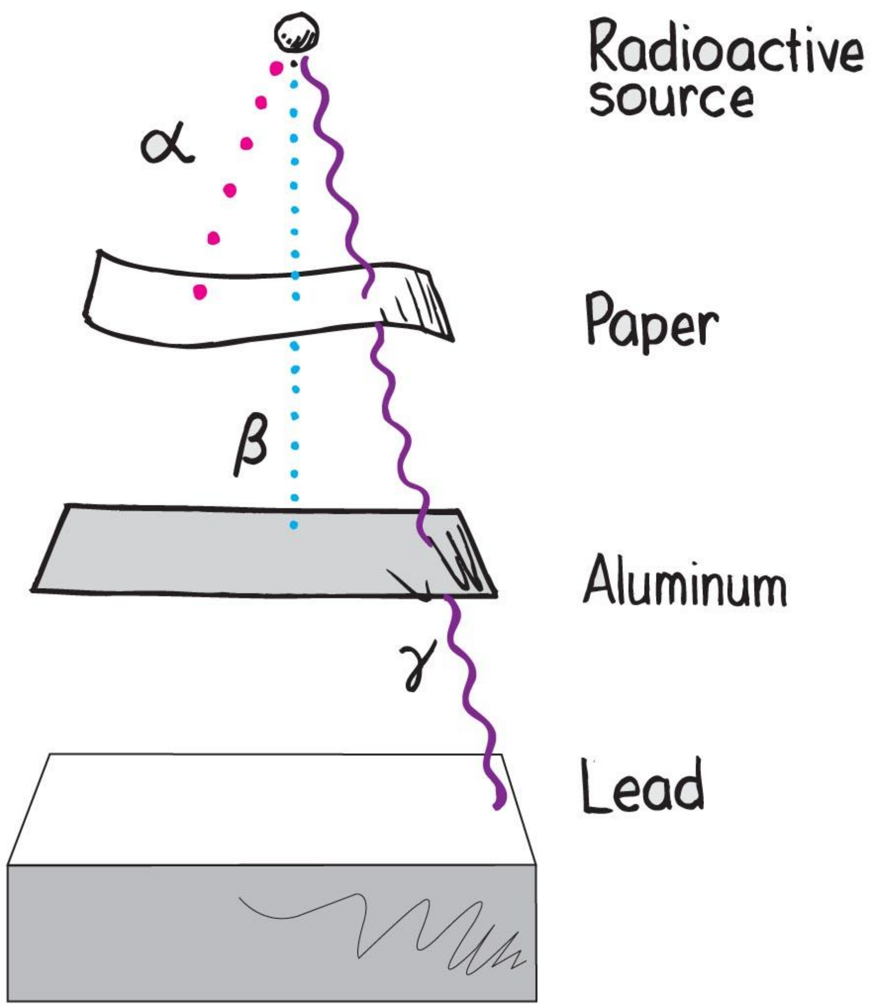
- Although we can’t actually see α, β, and γ radiation – we can see the effects of the radiation.

- For example, suppose you look in the sky after a jet flown overhead and off into the horizon. Although you cannot actually see the jet anymore, you can see the condensation trail left behind from the jet.

- Radioactive emissions also make trails if allowed to pass through a gas or liquid. The reason for this is because as the emissions rip through, they ionize a path of atoms in the gas or liquid.

-Each type of particle leaves a different path: For alpha particles the tracks are short and fat, for beta particles the tracks are skinnier, and for gamma rays the tracks are long and thin and difficult to detect.

See what it penetrates. A piece of paper can stop alpha rays. Beta particles can be stopped by a sheet of aluminum. Even lead may not stop gamma rays.



Ionizing Ability

- Recall that an ion is an atom which has become charged as an electron has either been added or stripped away.

- **Ionizing ability** can be thought of as the ability to strip electrons from atoms.

- Being the nucleus of a helium atom, an α particle is much more likely to knock an electron out of orbit when it hits a target atom.

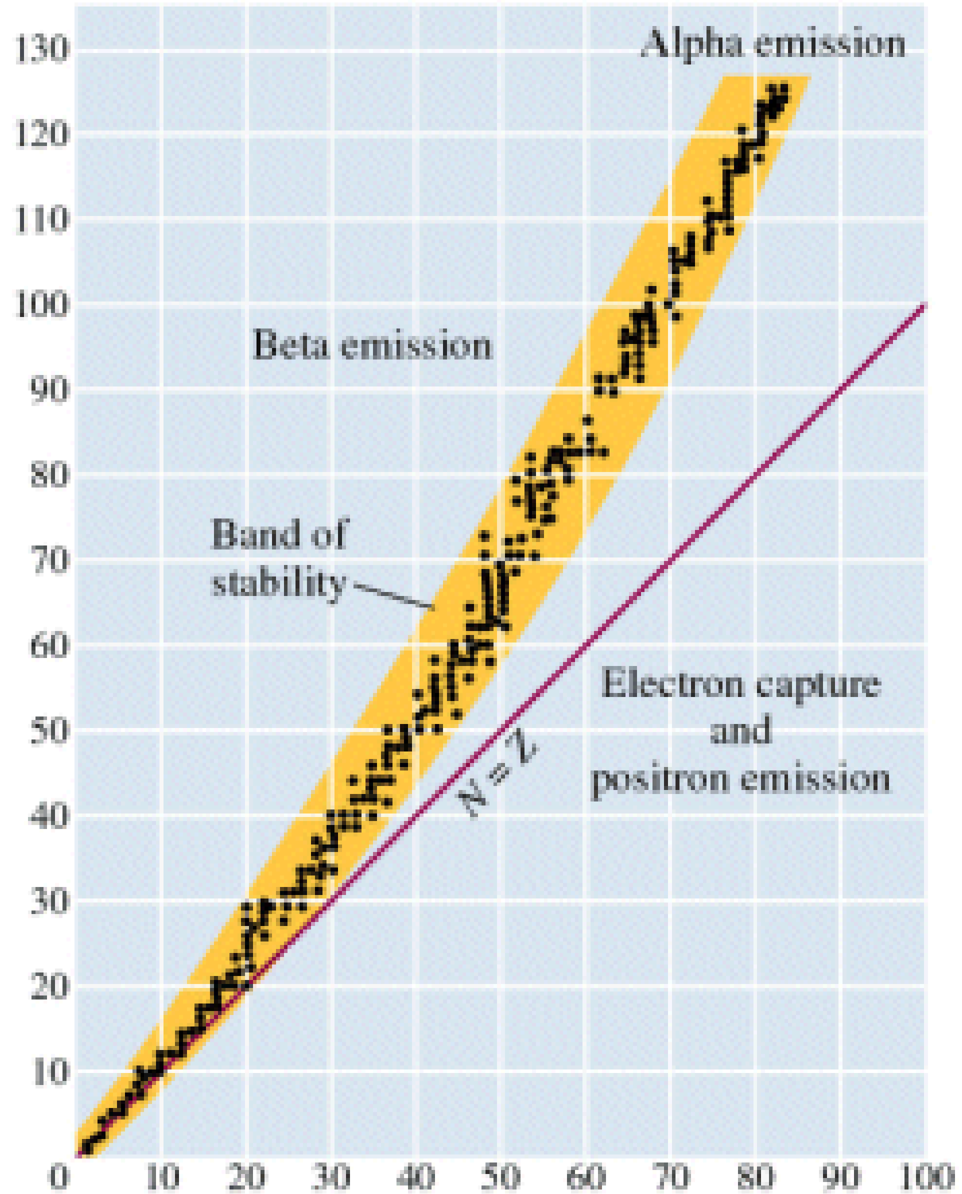
- β particles are most least likely to ionize target atoms because the β particles are thousands of times lighter than α particles.

- Relatively speaking, therefore, **alpha particles have the greater ionizing ability**.

- Since **gamma radiation has no mass and no charge, it has the lowest ionizing ability of the three emissions.**

Band of Stability

Number of Neutrons, (N)



Number of Protons (Z)

Ex - Determine the value of x and y in each nuclear equation where P = parent and D = daughter. Name the type of decay.

a) $^{212}_{82}P \rightarrow ^{212}_{x}D + ^{0}_{-1}e$

b) $^{210}_{84}P \rightarrow ^{y}_{x}D + ^{4}_{2}He$

c) $^{227}_{89}P \rightarrow ^{227}_{90}D + x$

d) $^{226}_{88}P \rightarrow ^{y}_{x}P + \gamma$

Ex - Determine the value of x and y in each nuclear equation where P = parent and D=daughter. Name the type of decay.

a) $^{212}_{82}P \rightarrow {}^{212}_{x}D + {}^{0}_{-1}e$

Since a β🖉 particle is produced, this is **β🖉 decay**

The atomic number of the daughter must be **x = 83**, since it increases by 1 for β🖉 decay.

b) $^{210}_{84}P \rightarrow {}^{y}_{x}D + {}^{4}_{2}He$

Since an α🖉 particle (helium nuclei) is produced, this is **α🖉 decay**

The atomic mass number of the daughter must be y = 210 – 4 = **216.**

The atomic number of the daughter must be x = 84 – 2 = **82**.

c) $^{227}_{89}P \rightarrow {}^{227}_{90}D + x$

A, the unified atomic mass, did not change, but the number of protons or positive charges increased by 1.

Therefore, **a neutron has decayed into a proton**. This means that **an electron was emitted from the parent nucleus.** This is **β- decay.**

x = $^{0}_{-1}e$

d) $^{226}_{88}P \rightarrow {}^{y}_{x}P + \gamma$

This is **gamma radiation.**

With the emission of a gamma ray the parent nucleus does not change.

That is, the atomic number and atomic mass number stay the same.

x = 88 and y = 226.

e) $^{214}_{83}P \rightarrow {}^{x}_{y}D + {}^{0}_{-1}e$

f) $^{x}_{y}P \rightarrow {}^{222}_{86}D + {}^{4}_{2}He$

g) $^{215}_{84}P \rightarrow {}^{211}_{82}D + x$

h) $^{3}_{1}P \rightarrow x + \gamma$

e) $^{214}_{83}\text{P} \rightarrow {}^{x}_{y}\text{D} + {}^{0}_{-1}\text{e}$

Since a β✐ particle is produced, this is **β✐ decay**

The atomic number of the daughter must be **y = 84**, since it increases by 1 for β✐ decay.

The unified *A*, the unified atomic mass, did not change so **x = 214**

f) $^{x}_{y}\text{P} \rightarrow {}^{222}_{86}\text{D} + {}^{4}_{2}\text{He}$

The α-particle, $^{4}_{2}\text{He}$, tells us that this is **α decay.**

x = 224 + 4 = **226**; *y* = 86 + 2 = **88**.

g) $^{215}_{84}\text{P} \rightarrow {}^{211}_{82}\text{D} + x$

A decreases by 4 and *Z* decreases by 2.

Therefore the emitted particle (*x*) must be

an α-particle $^{4}_{2}\text{He}$

This is **α decay**

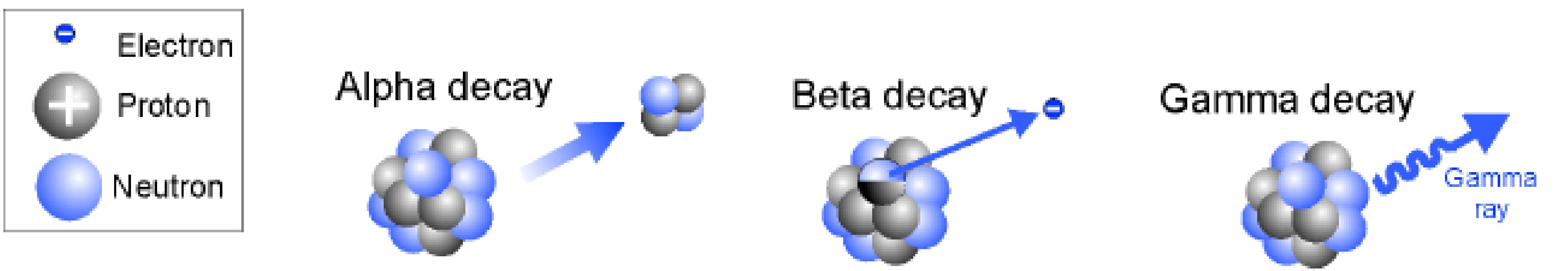
h) $^{3}_{1}\text{P} \rightarrow x + \gamma$

This is **gamma radiation**.

Because a gamma ray has no mass and no charge, the *A* and *Z* numbers of the parent nucleus do not change. $x = {}^{3}_{1}\text{P}$

Radioactivity Summary

- In alpha decay, the nucleus ejects two protons and two neutrons.
- Beta decay occurs when a neutron in the nucleus splits into a proton and an electron.
- Gamma decay is not truly a decay reaction in the sense that the nucleus becomes something different.



Protons	Decrease by 2	Increase by 1	Unchanged
Neutrons	Decrease by 2	Decrease by 1	Unchanged

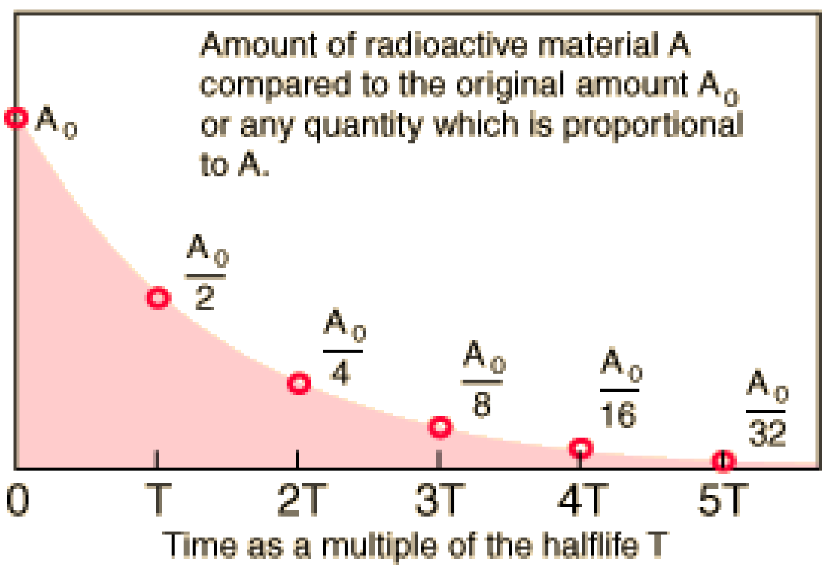
See worksheet

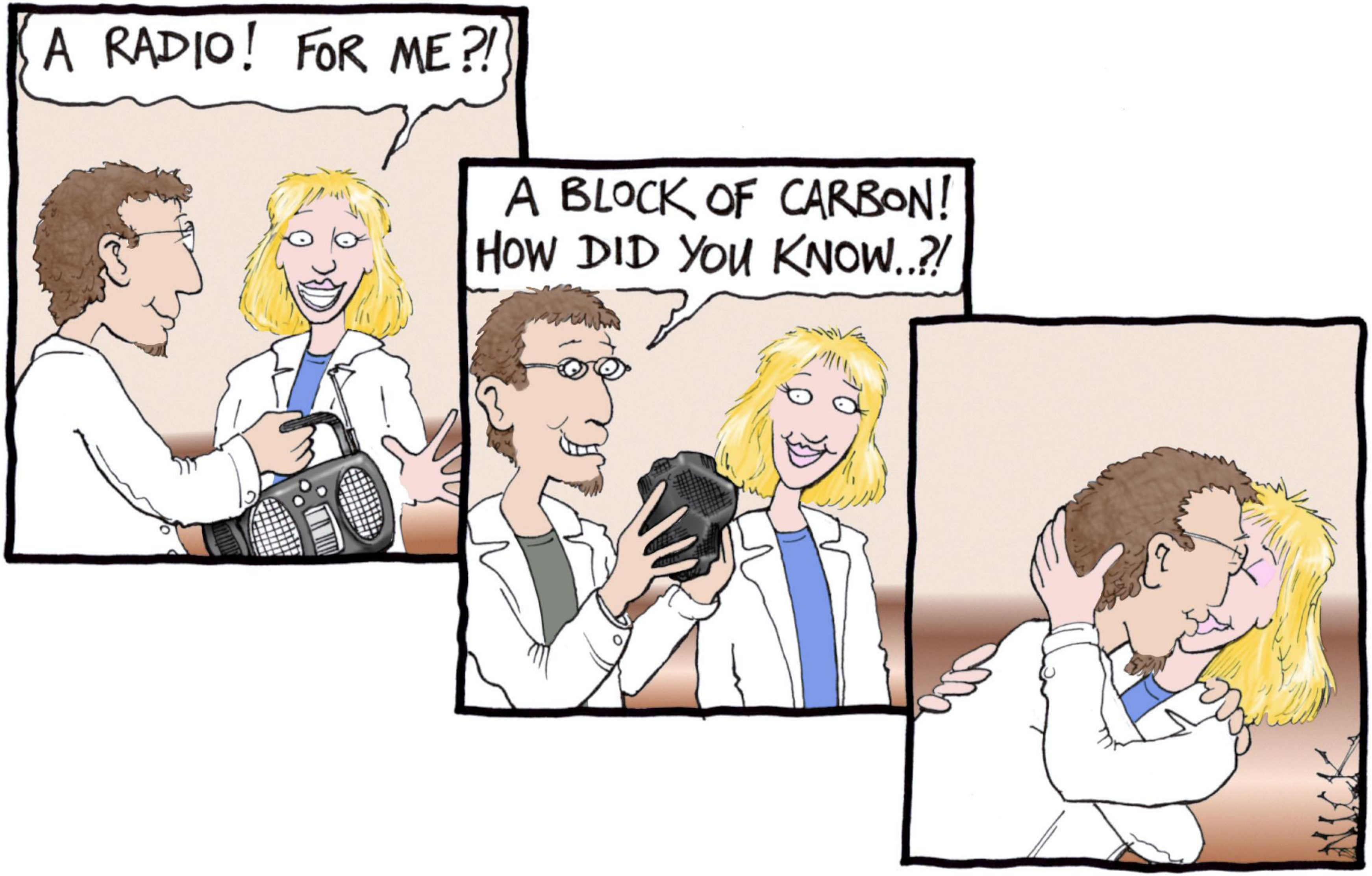
Natural Transmutation: Writing Equations for Decay

Physics 3204

UNIT 3: Section 8

Radioactive Half Life





The radiocarbon dating technique.

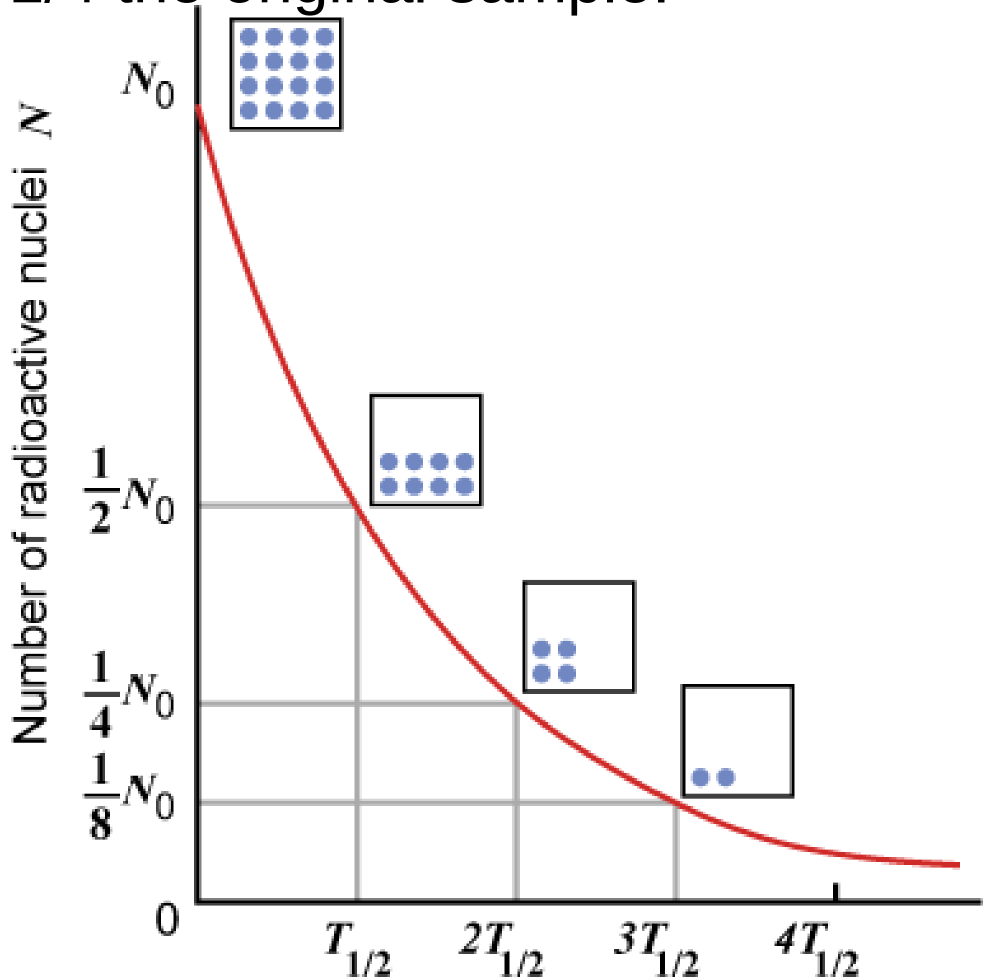
Graphical Representation of Half-Life – Exponential Decay

Half Life refers to the time for half of the radioactive nuclei in a given sample to undergo decay. After one half life there is 1/2 of original sample left. After two half-lives, there will be 1/2 of the 1/2 = 1/4 the original sample.

- The horizontal axis shows time – it is measured in number of half-lives.

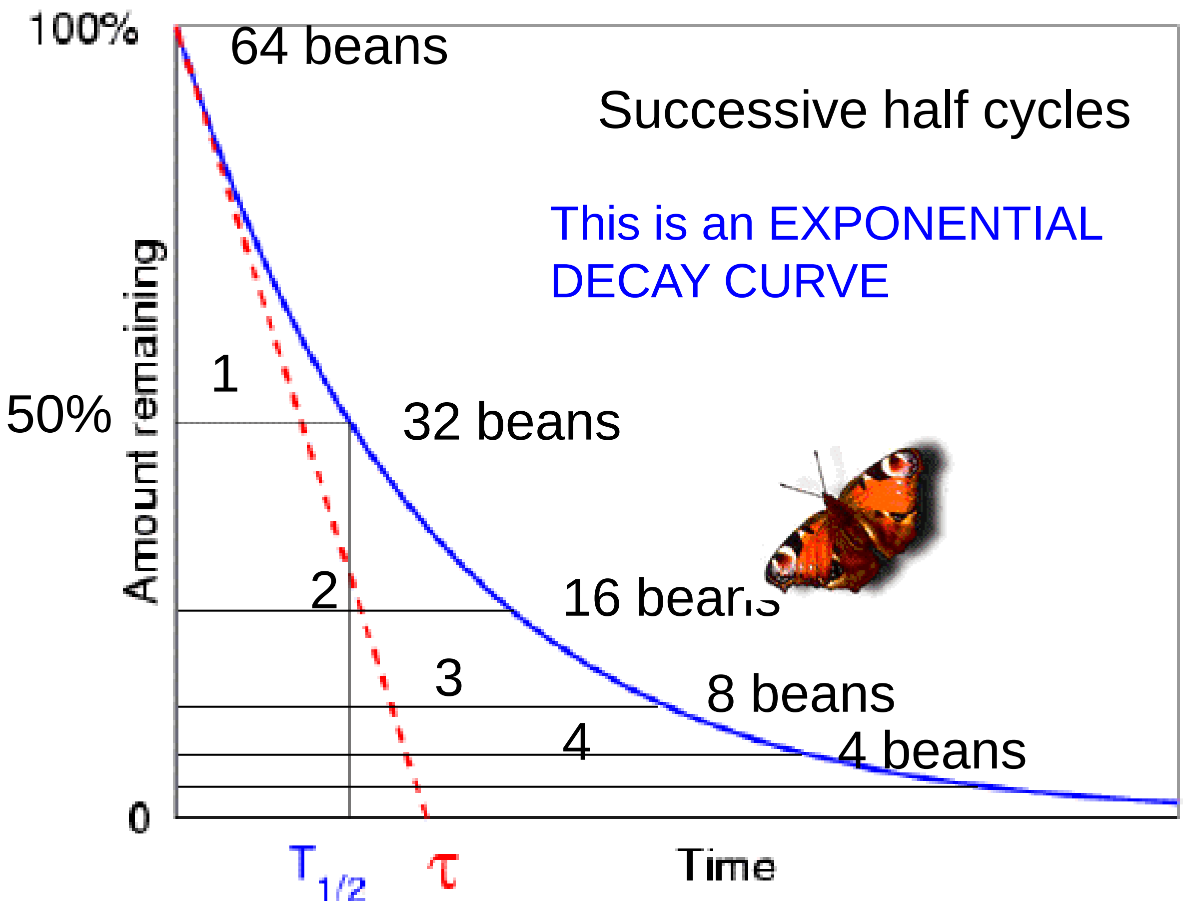
- The vertical axis shows the amount or material, or number of radioactive nuclei remaining after decay. (represented by blue dots in the squares).

- This is an example of an exponential graph.



Beanium decay

What does the graph of radioactive decay look like?



Mathematical Representation of Half-Life – Exponential Decay

-

- Mathematically, **radioactive decay can be calculated from the function:**

$$N = N_0 \left(\frac{1}{2} \right)^{\frac{t}{T_{1/2}}}$$

Where:

N = amount remaining after some time interval

N_0 = Initial amount (amount at time = 0)

$T_{1/2}$ = Half-Life of the particular isotope

Common Radioactive Isotopes

Isotope	*Half-Life*	*Radiation Emitted*
Carbon-14	5,730 years	β, γ
Radon-222	3.8 days	α
Uranium-235	7.0 x 108 years	α, γ
Uranium-238	4.46 x 109 years	α

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Given that the half-life of your bank account is 5 days, and the original amount is $1280, determine the number of dollars in your account after 20 days.

Solution A

Since 20 days represents 4 half-lives, divide 1280 by 2 repeatedly 4 times:

1280 ÷ 2 = 640; 640 ÷ 2 = 320; 320 ÷ 2 = 160; and 160 ÷ 2 = 80.

After 20 days the amount in the account is $80.00.

Here's a short-cut: dividing by 2 four times is the same as multiplying by ½ four times . That is:

$$\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \frac{1}{2^4} = \frac{1}{16}$$

$$\$1280 \times \frac{1}{16} = \$80$$

So, After 20 days, $80 remain.

Ex 1 - Given that the half-life of your bank account is 5 days, and the original amount is $1280, determine the number of dollars in your account after 20 days.

Solution B

Given:

No = 1280

t = 20 da

t(1/2) = half-life = 5 da

N = ?

$$N = N_0\left(\frac{1}{2}\right)^{\frac{t}{T_{1/2}}}$$

$$N = 1280\left(\frac{1}{2}\right)^{\frac{20\,days}{5\,days}}$$

$$N = 1280\left(\frac{1}{2}\right)^{4}$$

$$N = 1280\left(\frac{1}{2^4}\right)$$

$$N = 1280\left(\frac{1}{16}\right) = 80$$

Applying Decay to Atoms and Radioactivity

- **Activity** refers to the number of nuclei decaying per second
-

$$A = A_0 \left(\frac{1}{2} \right)^{\frac{t}{T_{1/2}}}$$

Where:

A = Activity remaining after some time interval t

A_0 = Initial activity amount (amount at time = 0)

$T_{1/2}$ = Half-Life of the particular isotope

For radioactive substances **the rate is given in becquerels** or **kilobecquerels (kBq)** or **megabecquerels (mBq).** One becquerel is 1 count/sec or 1/s or s^{-1}.

- For example, an activity 1.5 kBq means that the recording device detects 1500 atoms decaying in one second.

-.

Geiger counter is used to measure the activity of a radioactive material. It is a type of radiation detector invented to measure x-rays and other ionizing radiation, since they are invisible to the naked eye. It detects radiation such as alpha particles, beta particles and gamma rays It was invented by Hans Geiger.

Example 1:

A radioactive chemical has an activity of 10,000Bq. What is the activity of this chemical after 2 half-lives have passed?

Example 2:

A radioactive sample in a laboratory has a half-life of 10 days. If the sample has an activity of 4800Bq when it is returned to the safe, what will be it's activity when it is next used 40 days later?

Example 3:

Lead-212 has a half-life of 10.6 hr. If at noon the mass of a sample of lead-212 is 0.1 mg, what will be its mass at 3:00 PM?

Example 4:

The number of radioactive nuclei in a particular sample decreases over 15 days to 1/16 of the original number. What is the half-life of these nuclei?

Example 5:

The half-life of strontium-90 is 28 years. After 150 years, approximately what percentage of the material in the box would be strontium-90?

Example 6:

A piece of meteorite is observed to have a radioactivity with a half-life of 7.6 a. When first discovered, the radioactive activity was 8500 kBq. How many years will pass before its activity is 2500 kBq?

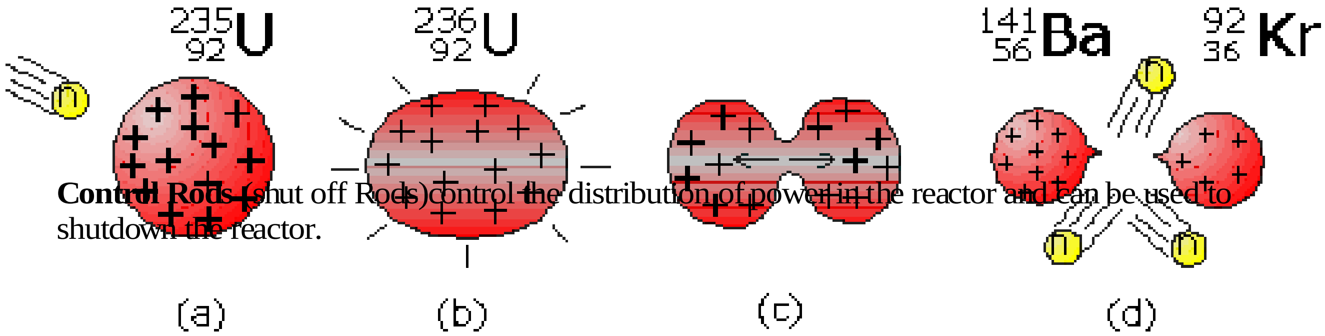
Physics 3204

UNIT 3: Section 9

Energy Production

Energy in Fission

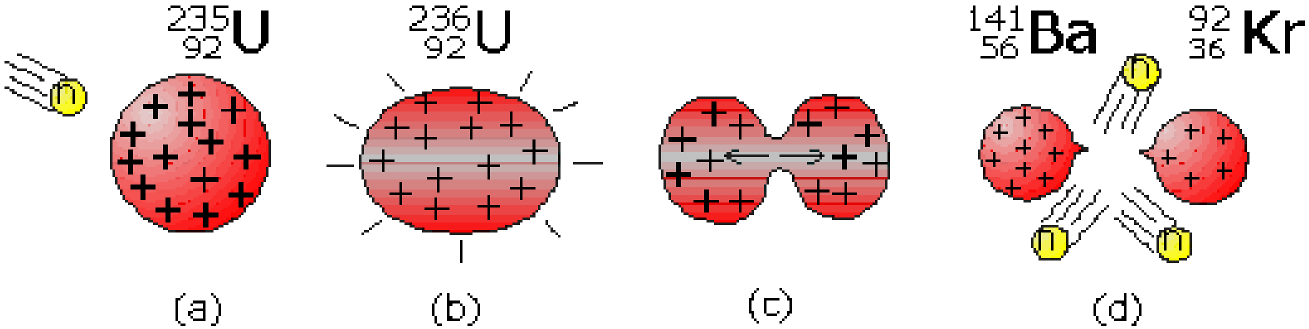
In 1938, Otto Hahn and Fritz Strassman discovered that when neutrons bombard uranium atoms, the uranium atoms split into two pieces. The picture below shows a typical splitting. The scientific name for the splitting of the uranium atom is **nuclear fission**.



Control Rods (shut off Rods) control the distribution of power in the reactor and can be used to shutdown the reactor.

(a) An incoming neutron is about to strike a uranium-235 nucleus.

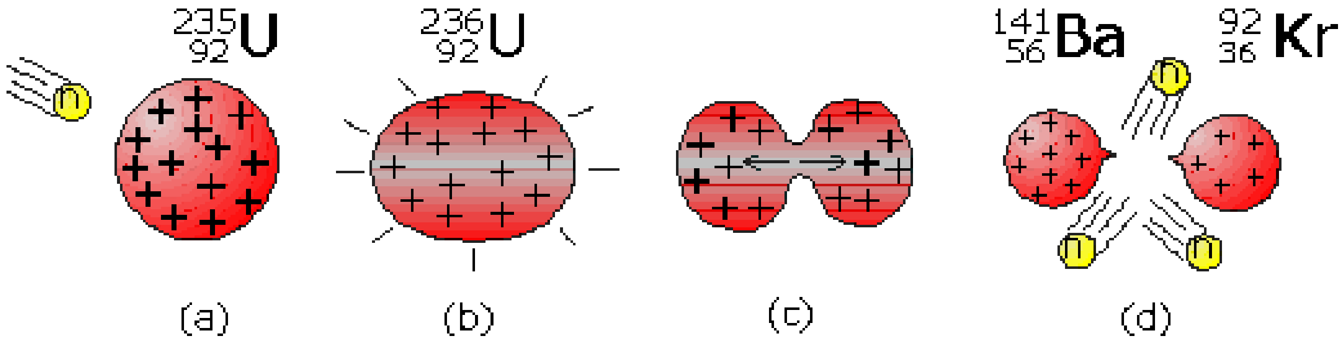
(b) After the neutron is captured by the uranium nucleus, the atomi mass number (*A*) increases by 1, but, because the neutron has no charge, the atomic number (*Z*) stays the same. This means that uranium-236 is an isotope of Uranium-235. The 236U nucleus is so excited that it lasts for less than 10-12 s



(c) In this excited state it becomes so elongated that the strong nuclear force loses its effect, and the repulsive electric force causes the nucleus to separate into two separate nuclei.

(d) The two new elements are Barium and Krypton. Note that 3 extra neutrons are also emitted. Under the right conditions these three neutrons will bombard 3 more uranium nuclei, each of which will release 3 more neutrons. Notice that one neutron produced three, three will produce nine, nine will be produce twenty-seven, and so on. In the blink of an eye, billions of nuclei will be split, and each time the mass of the fission products will be less than the mass of the uranium nucleus. This mass difference is changed to heat according to $E = mc^2$. The rapid growth in the production of neutrons and the subsequent fission process is called a **chain reaction**.

The reaction equation



Picture (a) → Picture (b) → Picture (d)

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{236}_{92}U \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3(^{1}_{0}n)$$

Practice exercise 1

Calculate the mass difference and the equivalent energy released in the nuclear reaction described above.

neutron .... 1.008665 u 235U .... 235.043924 u
141Ba .... 140.91440 u 92Kr .... 91.92630 u

Solution

Total atomic mass before the reaction is the mass of 1 neutron and one 235U nucleus. That's **1.008665 u + 235.043924 u = 236.052589 u**

Total atomic mass after the reaction is the mass of 3 neutrons, one 141Ba nucleus and one 92Kr nucleus. That's

3 (1.008665 u) + 140.91440 u + 91.92630 u = 235.866695 u.

The mass difference = 236.052589 u - 235.866695 u
= 0.185894 u.

Remember 1 u = 1.6605×10^{-27} kg.

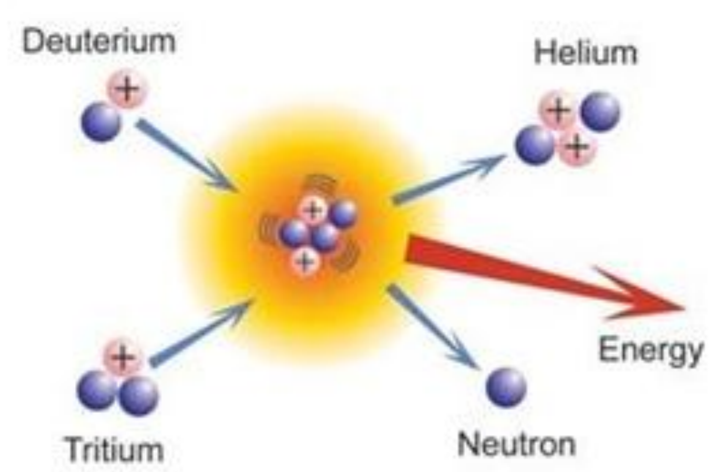
In kg's the mass difference is $0.185894 \times 1.6605 \times 10^{-27}$ kg = 3.08677 x 10-^{28} kg.

Now $E = mc^2$ = 3.08677 x 10-28 kg x (3.00 x 108 m/s)^2
= 2.78×10^{-11} J

Energy and Fusion.

It is believed that in the sun the temperatures and pressures are so great that hydrogen nuclei fuse into helium nuclei. The helium nucleus is lighter than the sum of the separate nuclei before the fusing. The difference in mass is converted into energy according to the expression $E = mc^2$.

An even simpler example of fusion involves a neutron fusing with hydrogen-1 to form the isotope hydrogen-2 plus gamma radiation. Another name for hydrogen-2 is deuterium. The reaction looks like this:



Practice exercise #2

In a fusion reaction, 2 atoms of deuterium (^2_1H) combine to form the helium isotope,

(a) Write a balanced equation to determine what other particle is produced.

(b) Given the following masses, calculate the energy released.

^2_1H 2.014102u

^3_2He 3.016029u

n 1.008665u

Solution

(a) The equation is $^2_1H + ^2_1H \rightarrow ^3_2H + ^1_0n.$

The *Z* numbers (the charge) is already conserved with *Z* = 2 on each side. However, the atomic mass (*A*) must increase by 1 on the RHS. Consequently, the missing particle must have a mass of 1, but no charge. The neutron is such a particle.

$$^2_1H + ^2_1H \rightarrow ^3_2H + ?.$$

(b) To compute the energy released, first determine the mass difference:

m = mass difference = (mass of left hand side) - (mass of right hand side)

= (2.014102 + 2.014102) - (3.016029 + 1.008665)

= 4.028204 - 4.024694

= 0.00351 u

Then use method 1 or method 2 of practice exercise 1 The answer is

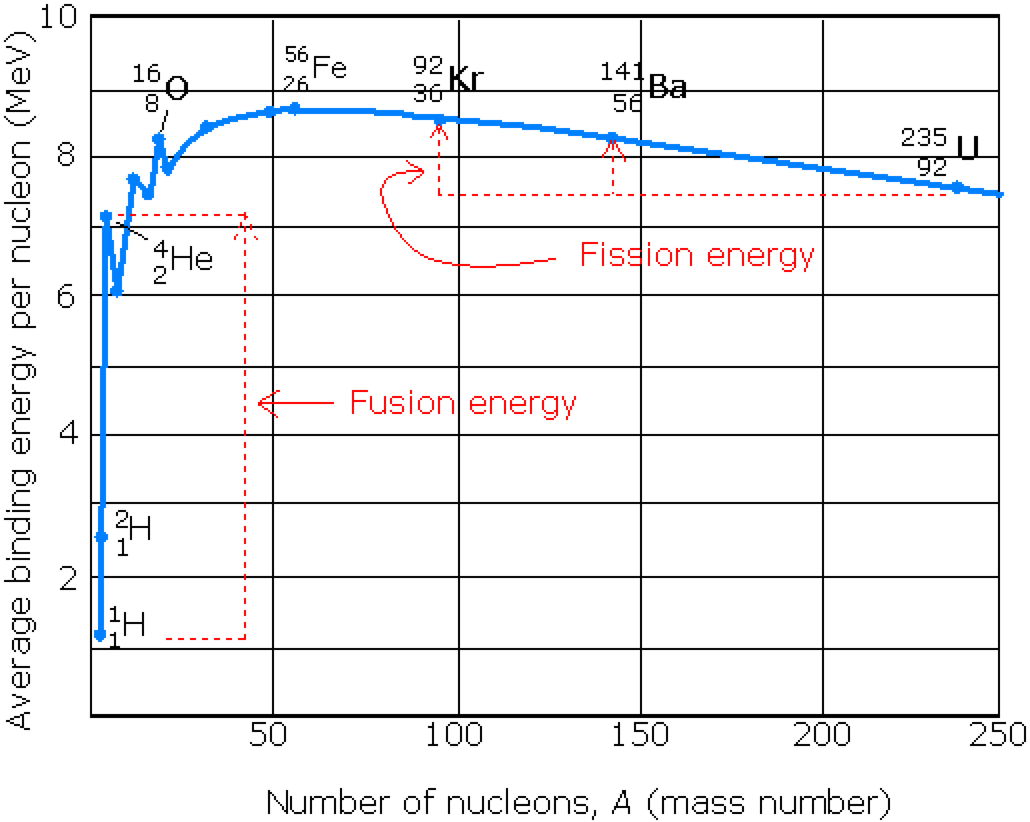
***E* = 5.25 X 10-13 J or 3.27 MeV**

Comparing Fission and Fusion

In one way nuclear fusion is the opposite of nuclear fission. Since in nuclear fission, a large nucleus splits into two smaller ones, in nuclear fusion two small nuclei join to make one larger one.

Both processes produce enormous amounts of energy. In fact fusion produces about 4 times as much energy as fission. This is illustrated in the graph.

The vertical arrows represent the change in binding energy as (i) hydrogen fuses into helium, and (ii) U-235 fissions into Ba-141 and Kr-92. Note that the change in binding energy for fusion is about 4 times the change in binding energy for fission.

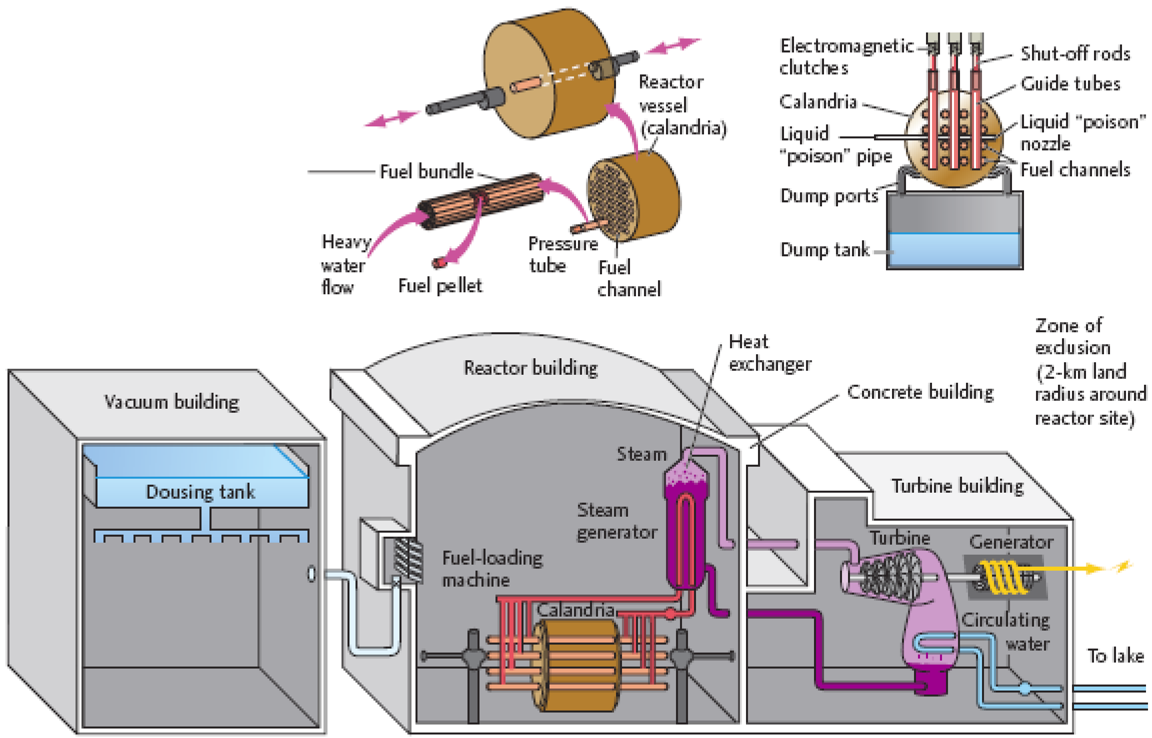


Why it is fission and not fusion that has been developed commercially.

You may be wondering why it is fission and not fusion that has been developed commercially. The reason is that it is much easier to achieve nuclear fission than nuclear fusion. This is because in order to make nuclei fuse, the repelling positive electric force on the protons must be overcome. One way to do this is to make the nuclei move very fast towards each other. And one way to make them move fast is to increase their temperature. Therein lies the problem. The temperatures required are similar to the temperatures in the stars and in our sun. That's in the order of a millions of degrees!! Such temperatures are difficult to achieve on earth.

Nuclear Fission Energy Production

CANadian Deuterium Uranium reactor **(CANDU)** gets energy from the fission of Uranium which occurs in its many fuel bundles.



Calandria is the reactor core that contains a moderator, and the nuclear fuel to achieve nuclear fission.

Nuclear fuel (natural uranium 235) is a material that can be consumed to derive nuclear energy

Moderator is a medium which reduces the velocity of fast neutrons.

Deuterium (Heavy water) is used as a moderator. Heavy water is chemically and physically identical to regular water, with the exception that the extra neutron in each atom of hydrogen makes it more dense.

Control Rods (shut off Rods)control the distribution of power in the reactor and can be used to shutdown the reactor.

Critical Mass: the minimum mass of nuclear material needed for a self –sustaining chain reaction to occur

Controlled Nuclear Fission Reactions

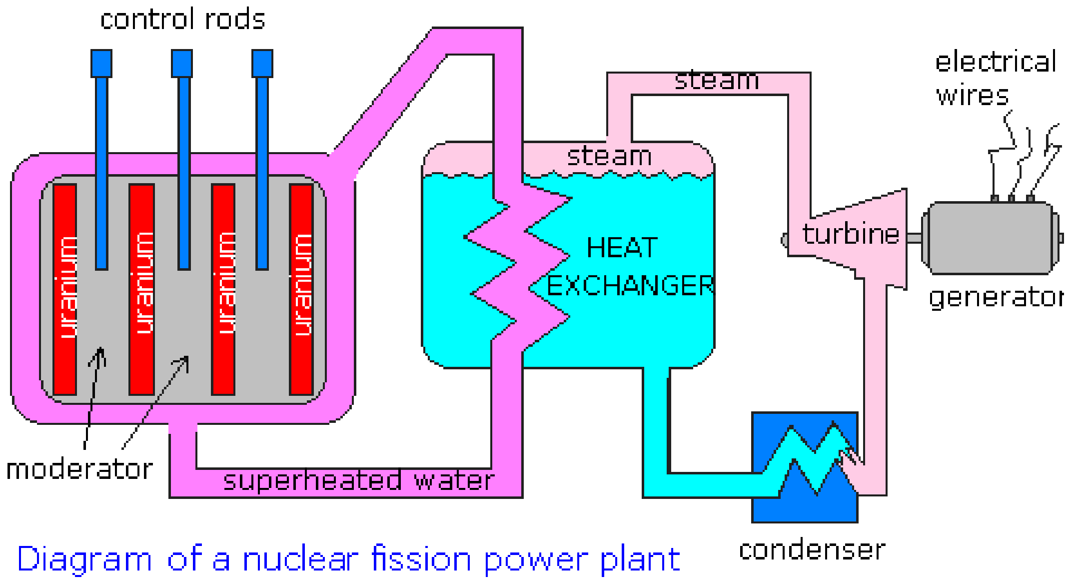


Diagram of a nuclear fission power plant (adapted from Conceptual Physics by Paul G. Hewitt)

The moderator slows down the neutrons so that the uranium atoms in the fuel rods will capture the neutrons and go through the fission process. The fission process produces enormous heat which superheats the water that surrounds the core. The superheated water is piped to a heat exchanger where it causes more water to boil and give off steam. The steam causes the blades of the turbine to spin. The turbine is connected via a shaft to the generator and electricity is produced. The steam is recycled via a condenser where it is converted back to water. The control rods are made of a material that can absorb neutrons. Consequently, the nuclear reaction can be controlled by raising and lowering the control rods.

CANDU Safety Systems

1)Moderator Dump -The heavy water moderator passes through the calandria by gravity. If no more heavy water is 'poured', the reactions stop because there is no moderator slowing down neutrons

2)Cadmium Control Rods - Cadmium rods, which absorb neutrons, can be lowered into the core remotely to control the reactions. These rods are dropped from electromagnetic clutches and stop the reactions, if there is a power outage.

3) Moderator "Poison" - A neutron-absorbing solution can be injected into the moderator. This stops the chain reactions, while also cooling the core.

Nuclear Energy Debate

Reasons for Nuclear Energy

1)The demand for electricity will keep increasing, so the way in which we generate electricity must be able to keep up

2)Uranium, the fuel for nuclear fission, is indigenous to which frees us from depending on expensive importing of oil and natural gas.

3)Everything we do involves risk , and there is certainly no way to generate the power that we need risk free. The safety of CANDU reactors has been proven and is a technology that is available now

4)Compared to burning coal, CANDU reactors are much more environmentally friendly.The highly radioactive waste that is produced does not take up much volume

5) High capital costs at the outset will be more than offset by a plenitude of safe and inexpensive power for years to come.

Reasons Against Nuclear Energy

1) Energy conservation and efficiency improvements could reduce the growth rate for electricity demand while at the same creating jobs

2) Uranium mining in Canada disturbs buried radioactive material. Exposed radioactive material is called **radioactive tailings.** It leaches into the soil and groundwater, causing radioactive contamination of sensitive ecosystems

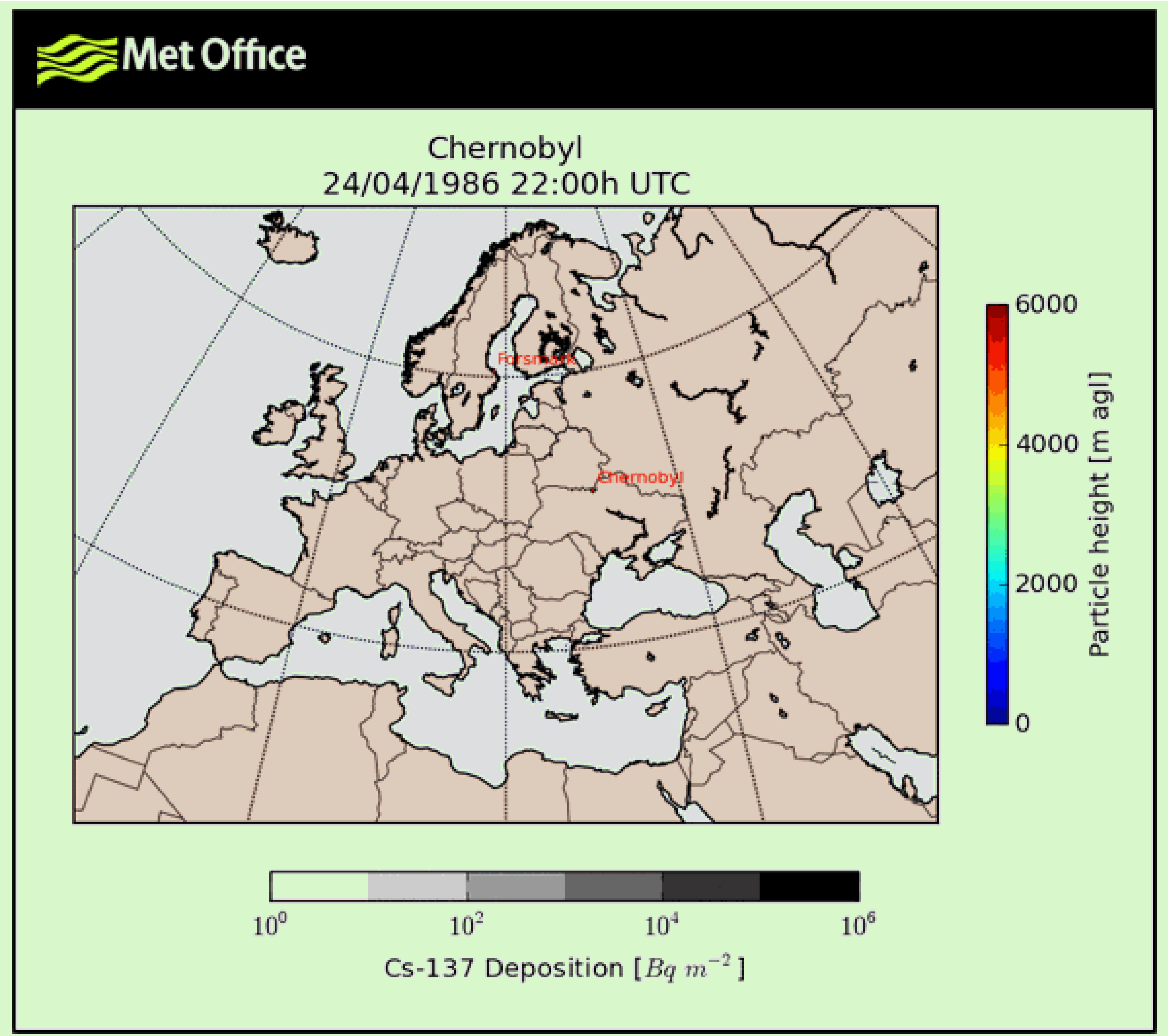
3) Any safety record has been based on limited operational experience. Any health and environmental effects may take years to manifest themselves, when they do, the result is long term and catastrophic

4) The nature of the effects of exposure to radioactive isotopes means that any negative health and environmental effects will not be realized for years. No permanent and safe methods for the disposal of long-lived high-level radioactive have been employed as of yet

5) Nuclear power is very centralized and capital cost intensive. Quite often, the costs may be hidden due to various government subsidies


1.8 MW
ZERO EMISSIONS
450 MW X 6 = 2700 MW
ZERO EMISSIONS
ANY QUESTIONS?




Met Office
Chernobyl
24/04/1986 22:00h UTC
Forsmark
Chernobyl
6000
4000
2000
0
Particle height [m agl]
10^0
10^2
10^4
10^6
Cs-137 Deposition [Bq m^-2]

See the worksheet on fusion:

Mass-Energy Equivalence and the Process of Fusion

Congratulations you are DONE!