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Physics Module 8

From the Universe to the Atom

Topic Outline

1. Origin of the Elements
- The Big-Bang & expanding Universe
- How the first matter was formed
- Formation of stars & galaxies
- The Hertzsprung-Russell diagram
- Fusion reactions in stars
- Life stages of stars & nucleosynthesis

2. Structure of the Atom
- Cathode rays & Dalton's atom
- Thomson's expt. & the electron
- Millikan's oil-drop expt.
- Geiger-Marsden expt. & Rutherford's model
- Chadwick's discovery of the neutron

3. Quantum Mechanical Nature of the Atom
- Problems with the Rutherford atom
- Balmer Series. Rhydberg equation
- The Bohr model of the atom
- De Broglie's matter-waves
- Contributions of Heisenberg, Pauli & Schrodinger

4. Properties of the Nucleus
- Nucleons, nuclei & isotopes
- Radioactivity.
- Mechanisms of decay. Properties of α, β, γ
- Rate of decay
- Nuclear fission
- Mass defect in nuclear reactions

5. Deep Inside the Atom
- Four fundamental forces
- Finding the fundamental particles
- Outline of the "Standard Model"

What is this topic about?

To keep it as simple as possible, (K.I.S.S. Principle) this topic covers:

1. Origin of the Elements
The Big-Bang Theory & expanding Universe. How matter was first created. Formation of stars & galaxies. Classification of stars & the Hertzsprung-Russell diagram. Fusion reactions in stars. Life stages of stars & nucleosynthesis.

2. Structure of the Atom
The mystery of cathode rays. Dalton's atomic model. Thomson's experiment. Discovery of the electron. The "Plum-Pudding" model of the atom. Millikan's oil-drop experiment. The Geiger-Marsden experiment. Rutherford's atomic model. Chadwick's experiment and discovery of the neutron.

3. Quantum Mechanical Nature of the Atom
Problems with the Rutherford atom. The Balmer Series of spectral lines & the Rhydberg equation. The Bohr atom explains it all, but has some limitations. De Broglie & "matter waves". Development of Quantum Mechanics. Contributions of Heisenberg, Pauli & Schrodinger.

4. Properties of the Nucleus
Nucleons & nuclei. Isotopes. Radioactivity. Mechanisms & equations for alpha & beta decay. Properties of alpha, beta & gamma radiations. Rate of decay. Half-life & decay constants. Nuclear fission. Mass defect in nuclear reactions.

5. Deep Inside the Atom
The 4 fundamental forces. Finding the fundamental particles. Importance of the "atom-smasher" experiments. Outline of the "Standard Model of Matter".

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1. Origin of the Elements

To understand where atoms and the chemical elements came from, we must start with the beginning of the Universe itself. Our best explanation of that, is known as "The Big-Bang Theory".

Outline of the "Big-Bang" Theory

1. The universe began 13.8 billion years ago.

2. In the beginning, all the space, matter and energy of the universe was concentrated in a "singularity"... one tiny point of incredible density and temperature.

3. This exploded outwards in all directions, becoming cooler and less dense as it expanded very rapidly. This expansion is still occurring today. Galaxies are moving further apart as the space between them expands.

Note: You must NOT think of this as if the matter exploded outwards into the space surrounding it.

The explosion and expansion was of space-time itself. Before the explosion there was no space or time.

4. Within a galaxy, gravity attracts matter and holds stars and planets together in their orbits around each other, so there is no apparent expansion noticeable in the "local" area of space.

This theory seems strange and unbelievable when described in simple outline, so why is it accepted as being correct? Simple! ...because the theory explains many observed facts about the universe:-

What the "Big-Bang" Explains

The Universe is expanding

The main evidence is the "Red-Shift" of the spectral lines of distant galaxies. This can only be explained by a continuing expansion of space-time due to the original explosion.

Explanation of the "Red Shift"

The "Cosmic Background Radiation"

It was discovered in 1965 that the entire Universe seems to be filled with microwave radiation coming from every direction. This is explained as being the "afterglow" of radiation from soon after the Big-Bang occurred.

What the Universe is Made From

The observed chemical composition of the universe (almost entirely hydrogen and helium) agrees with theoretical predictions of what should have happened during the first seconds of the Big-Bang.

Discovery of the Expanding Universe

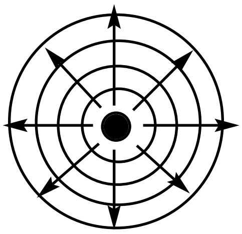
In 1922, the Russian Alexander Friedmann predicted that the universe should be expanding.

His prediction arose from working on the equations of Einstein's "General Theory of Relativity". This was a brave prediction at the time, since other galaxies beyond ours had not been discovered, and there was no known evidence of expansion.

During the 1920's new, bigger telescopes led to the discovery of other distant galaxies. The American, Edwin Hubble, analysed the spectral lines from distant galaxies and discovered the "cosmological red-shift". (A more detailed account of this was given in Module 7... revise if necessary.)

What is the "RED-SHIFT"?

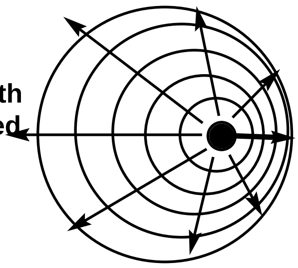
The "Red-Shift" is when the lines in a galaxy's light spectrum have "stretched" to longer wavelengths... nearer to the red end of the visible light spectrum.



This can be related to the *Doppler Effect*:
The waves emitted by a stationary object spread out evenly in all directions, with the same wavelength.

However, when the object is moving, the waves in front get "bunched up" and their wavelength is shortened. The waves behind get "stretched" and the wavelength is lengthened.

Light Waves Spreading Out From a Moving Galaxy



The Red-Shift in the light from distant galaxies seems to be caused by the expansion of space-time between them & us. The wavelength of light gets longer (redder). If they were approaching, we would see a "blue shift" in the light.

All distant galaxies show a red-shift.
It seems to be a fact that space-time is expanding.

Within the last 20 years new evidence has emerged that the rate of expansion of the Universe is actually increasing. The evidence has come from the study of supernova explosions in extremely distant galaxies and was discovered by an Australian astronomer, Brian Schmidt. For this, he was awarded the Nobel Prize.
No-one yet knows what is causing the expansion to accelerate, so for the moment astronomers refer to a phenomenon called "dark energy" while they continue to try to figure out how the Universe works.

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How the Matter of the Universe was Formed

By 1915, Albert Einstein had deduced his famous equation

$$E = mc^2$$

E = energy,
m = mass
c = the speed of light = 3×10^8 ms^{-1}

The equation predicts that matter and energy are equivalent and inter-changeable.

Because the c^2 term in the equation is a very large number, it follows that a very small amount of matter is equivalent to a large amount of energy

For example, during a nuclear explosion a small amount of matter "disappears". It has been converted into the energy of the explosion. In the Sun, as in all stars, energy is constantly being released from the conversion of matter to energy.

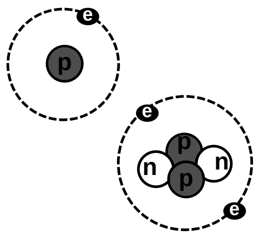
The reverse happened during the Big-Bang. Originally there was only energy. The matter and mass of the universe was formed from this energy, according to Einstein's equation. Obviously it must have taken large amounts of energy to form each tiny particle of matter.

In the first fraction of a second of the Big Bang explosion, all the "substance" of the universe was radiation energy. It was too hot for matter to form, or rather, any matter that formed was instantly torn apart again at a temperature of some billions of ^oC.

As the fireball expanded, however, it cooled rapidly until particles of matter (protons, electrons & neutrons) were "condensed" from the energy according to $E=mc^2$. This began about 1 second after the initial period of hyper-expansion.

A few minutes later, some protons & neutrons were able to combine into simple atomic nuclei.

After approximately 400,000 years it became cool enough for electrons to combine with nuclei to form the first atoms of mainly hydrogen, with some helium and a trace of lithium.



The atoms formed were nearly all hydrogen, with a small amount of helium and a trace of lithium

Formation of Stars and Galaxies

As the early universe (now made up of large amounts of atoms) continued to expand, it also cooled further. At this time the entire universe may be pictured as a single, hot cloud of mostly hydrogen gas, still expanding as space-time itself grows.

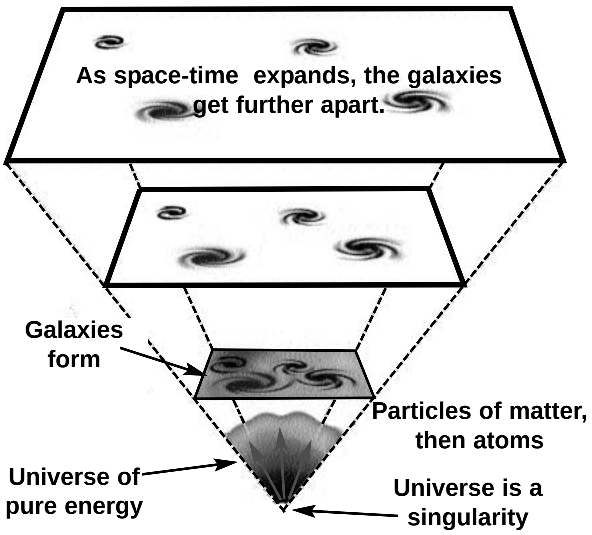
Expansion of a gas causes it to cool, so the temperature of the fireball must have fallen as the cloud expanded. Since temperature is really a measure of the kinetic energy (i.e. speed) of the particles, it follows that the KE of the atoms must have dropped too.

Eventually, the particles became cool enough (and slow enough) for gravity to have an effect.

If the atoms in the cloud had been perfectly evenly distributed, then gravitational attractions would have been equal in every direction and cancelled out. However, it seems that random fluctuations within the cloud had caused a degree of "lumpiness".

Note: we know this is true because the Cosmic Background Radiation (the afterglow of the Big Bang fireball) shows distinct patterns of unequal distribution.

Gravity was able to attract the matter within each "lump" of gas and cause it to collapse in on itself. Eventually, each separate "lump" of matter became a galaxy. Further "accretion" of "lumps" within each galaxy led to the formation of stars. Later, the debris of exploded stars, containing heavier elements, accreted to form solar systems like ours.



Roughly 14 billion years later, here we are on a planet, in a solar system, orbiting a star. Our star is one of billions, orbiting around our galaxy. Our galaxy is one of billions, all flying apart from each other as space-time itself continues to expand. Our bodies, and the Earth itself, are made up of atoms which were either created in the Big-Bang, or manufactured in a star. We are all "star material".

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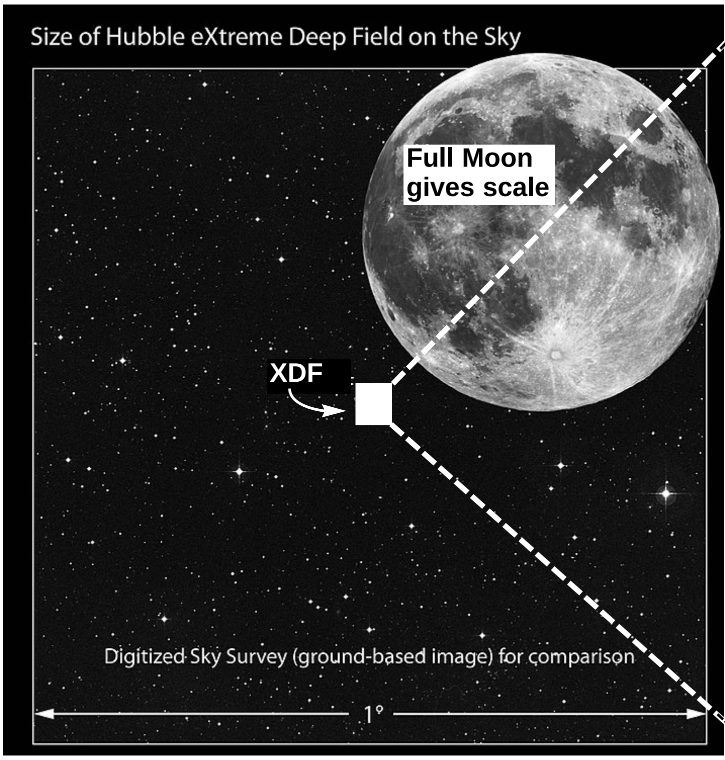
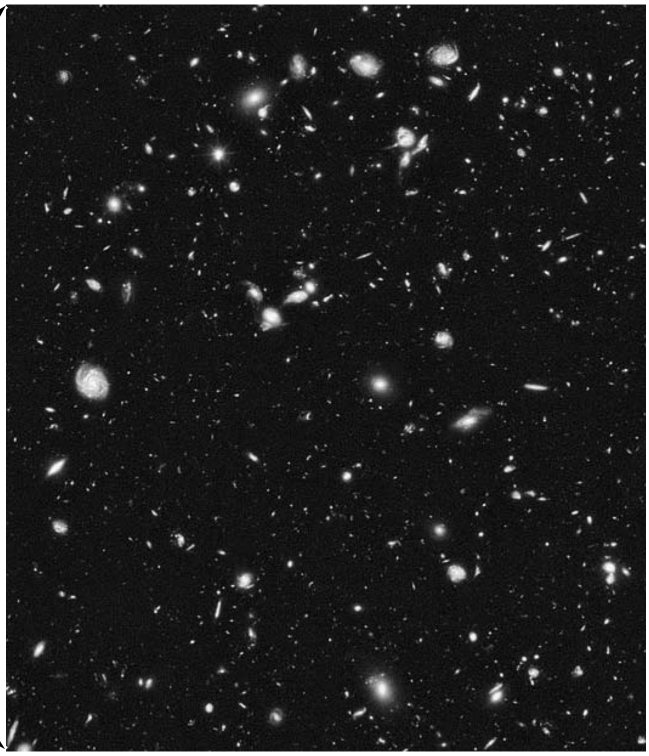
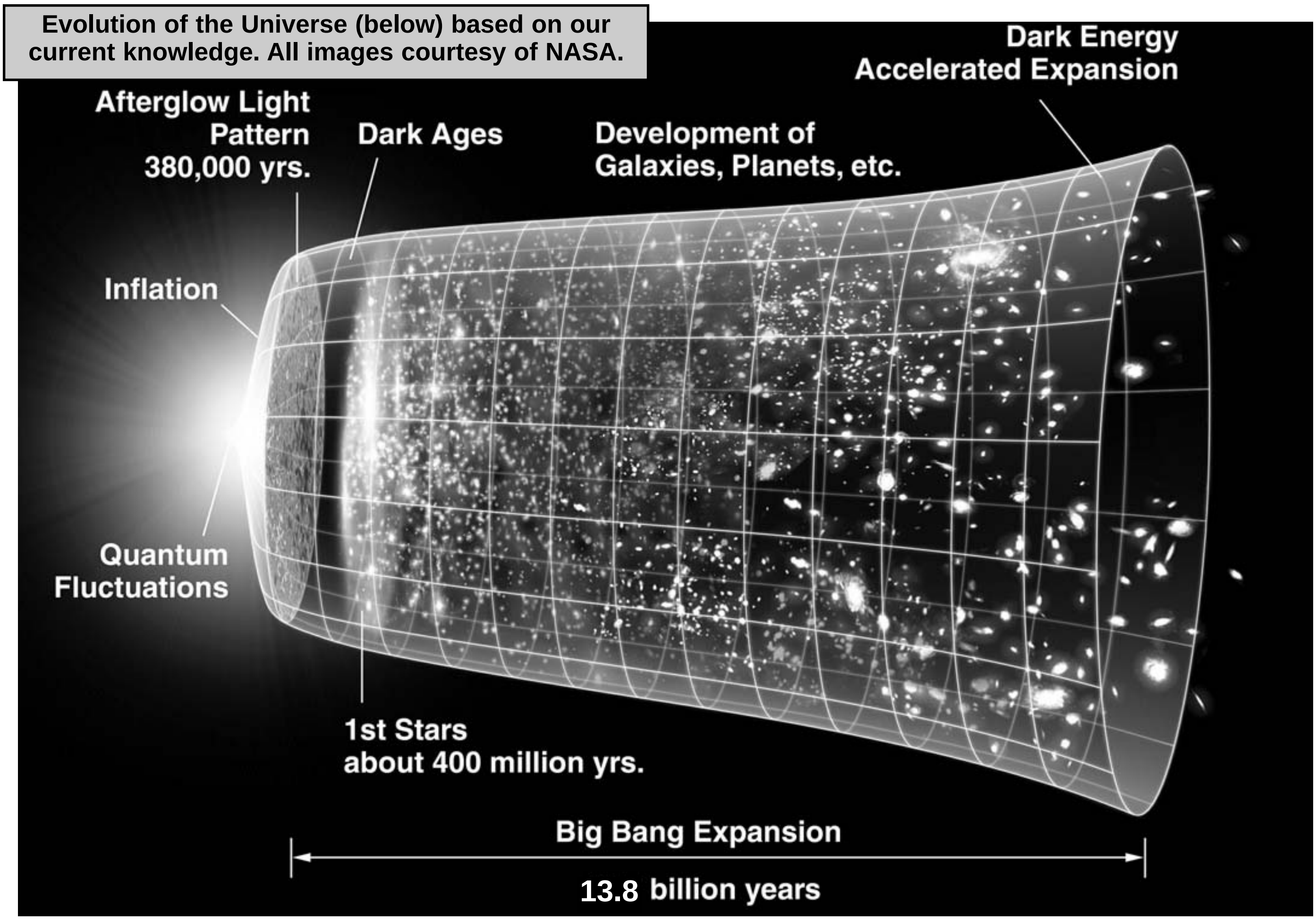
Images from Near the Big-Bang





The Hubble eXtreme Deep Field (XDF) views shown above are the result of combining 10 years of photos from the Hubble Space Telescope. At right is the deepest view of the Universe we have. The blobs of light are distant galaxies, some of which (the smallest) show the image of things from 13.2 billion years ago. We are looking back in time to the Universe as it was soon after the Big-Bang!

Evolution of the Universe (below) based on our current knowledge. All images courtesy of NASA.



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How Stars Make the Elements

Soon after the Big-Bang, the Universe was composed of hydrogen, a little helium & a trace of lithium. So, where have all the rest of the elements in the Periodic Table come from?

To answer that, you need to know more about the life and death of stars.

Begin with some material already covered in Module 7.

Revise Wien's Law (p.15 of KISS mod.7) and all the material on light spectra, intensity-wavelength graphs, star classification, etc. on pp. 5-8 inclusive.

The "Spectral Star Classification" scheme is important here, so we have reproduced it at the right.

Spectral Star Classification

Spectral Class	Colour	Surface Temp (K)	Spectral Features
O	Blue	>30,000	Strong ionised Helium
B	Blue-White	15,000 to 30,000	Strong neutral He lines
A	White	10,000 to 15,000	Prominent hydrogen lines
F	White-yellow	7-10,000	Strong metal lines and weak H lines
G	Yellow	5-7,000	Prominent Ca^{2+} lines
K	Orange	3,500-5,000	Strong lines from metals
M	Red	2,500-3,500	Strong lines due to molecules

To remember, use this mnemonic:
"Oh, Be A Fine Girl (Guy), Kiss Me".

Brightness & Magnitude of Stars

Over 2,000 years ago the Greek philosopher Hipparchus observed and mapped the star-field of the night sky. As part of his study, he invented a "scale of brightness" to classify each star he mapped. His scale was:

Brightest star visible = "magnitude 1"
2
3
4
5
Dullest star visible = "magnitude 6"

Note that this is a reverse scale... brighter stars have smaller number values.

For historical reasons, we still use this scale of magnitudes, but it is now mathematically defined and extended beyond the original 6 values. Telescopes have revealed faint stars not visible to the eye, so magnitudes 7,8,9,10... etc are included, and some stars are brighter than "magnitude 1", so values of 0, -1, -2, etc are included.

The magnitude scale is not linear.
By modern definition magnitude 1 is 100x brighter than magnitude 5, so (without going into the maths) each magnitude is different by about 2.5 times the amount of light intensity.

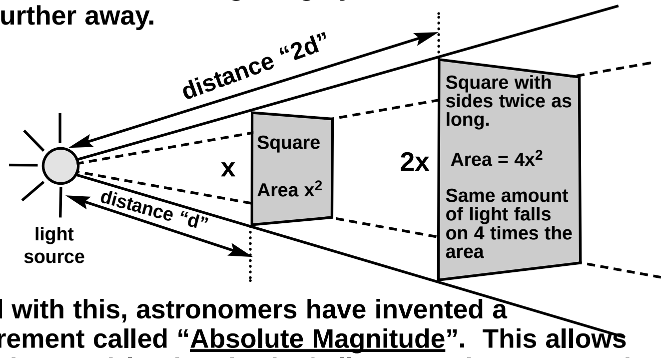
So, when we see a bright star (e.g. magnitude 1) in the sky it might be a small, dull star which is relatively close to Earth, or it could be a huge, highly luminous star which is much further away.

Magnitudes & Distance

The magnitudes dealt with so far are the "apparent magnitudes" of a star as seen from Earth. This value depends on how luminous the star really is and how far away it is.

You are reminded of the Inverse Square Law for how the brightness (intensity) of light energy drops off with the square of the distance. (diag. right)

This means, for example, that if 2 stars have the same luminosity (i.e. both emit the same amount of light energy), but one is twice as far away, it will appear only 1/4 as bright. If it was 3 times as far away it would be only 1/9 as bright, and so on.



To deal with this, astronomers have invented a measurement called "Absolute Magnitude". This allows the brightness ("luminosity") of all stars to be compared equally by calculating what magnitude they would have if viewed from a standard distance.

On the diagrams & graphs on the following pages, all the scales of "luminosity" are based on these "Absolute Magnitudes".

As an example, our Sun's absolute magnitude = +3.

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The Hertzsprung-Russell Diagram

The Hertzsprung-Russell (H-R) diagram is a graphical plot of the absolute magnitude of stars against their "spectral class", which relates to their surface temperature. It is named after the 2 astronomers who discovered the relationship around 1910.

Be careful trying to read this as a graph. Neither scale is linear and the temperatures of the horizontal scale decrease to the right.

Obviously, there is a pattern revealed in the H-R diagram and the reason for the pattern is the mass of each star.

Basically, low-mass stars are dim, cool & red. As you move upwards to the left along the "Main Sequence" of stars, they become hotter & brighter with "peaks" of radiation at higher frequencies. How does this work?

The more massive a star is, the greater the effect that gravity will have on it. More mass causes its core to be compressed inwards to a higher temperature & pressure, so that its matter becomes a hotter plasma and it "burns" hotter & faster.

What is a "Plasma"?

You may know that in Biology, "plasma" is the liquid part of the blood. Well, we are talking about something totally different here!

Plasma may be described as the "4th state of matter"...

SOLID $\xrightarrow{\text{heat}}$ LIQUID $\xrightarrow{\text{heat}}$ GAS $\xrightarrow{\text{heat}}$ PLASMA

If a gas gets hot enough, the atoms begin to lose electrons... they become ionised. A gas which is so hot that it becomes partially or completely ionised is called a "plasma".

If completely ionised, the plasma becomes an incandescent mixture of electrons and "naked" atomic nuclei. On Earth, a plasma can occur, (eg in the thin channel of air in a lightning discharge) but it quickly expands, cools and returns to the gas state.

However, in the core of a star, the plasma cannot expand & cool because of the enormous pressure of gravity pressing in. The temperature is millions of ^{o}C, so the bare atomic nuclei have a lot of KE and travel very fast. They slam into each other so hard that some of them undergo nuclear fusion.

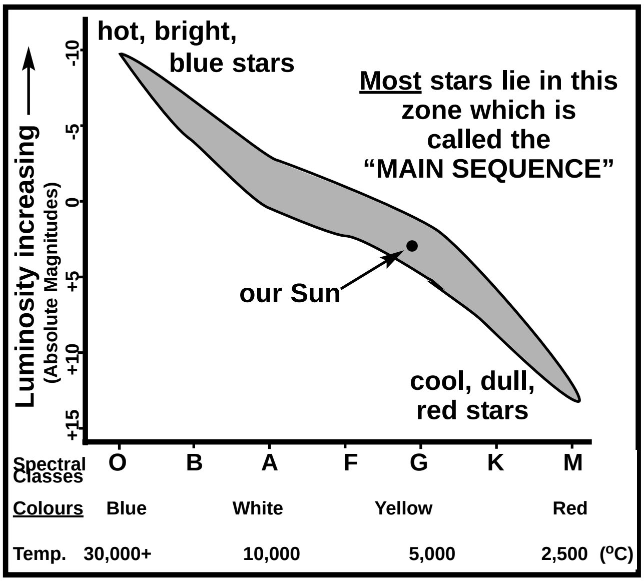
The size of any star is the balance between 2 opposing forces:

• Gravity, which attempts to collapse and compress the star inwards, and

• Heat and Radiation Pressure, from the energy released by nuclear fusion in the core. This would cause the star to explode outwards if not for gravity.

There are 2 fusion reactions you need to know about.

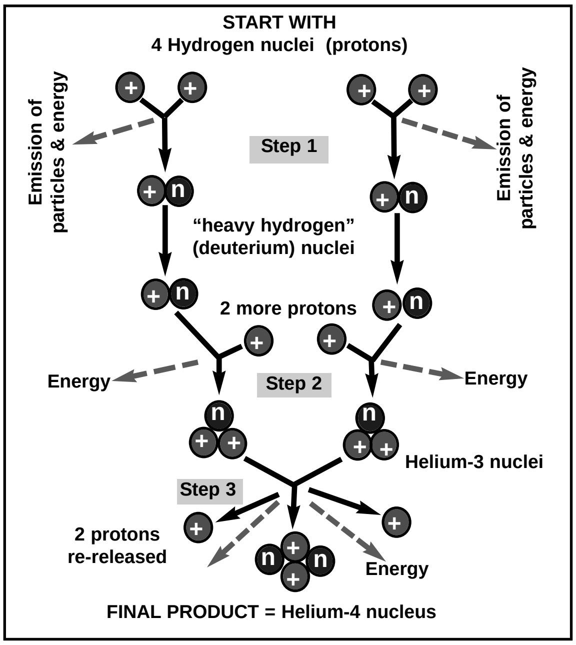
To an astronomer, the Sun is an average "Main Sequence" star, classified "G3" on the H-R diagram. (Spectral class "G", Abs.Mag = +3)



Note: Temp scale decreases to the right

The Proton-Proton Chain

This is the "classic" fusion of hydrogen into helium and is particularly important in small to medium sized stars.



The details of reaction steps 1, 2 & 3 are shown on the next page.

The immediate thing for you to realise is that the overall reaction turns protons (hydrogen nuclei) into helium and releases energy along the way.

Although not obvious in the diagram, the mass of helium at the end, is slightly less than the starting mass of hydrogen. This "mass defect" has been converted to energy according to $E = mc^2$.

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Fusion in Stars *(cont.)*

The Proton-Proton Chain (cont.)

Step 1:
Two hydrogen nuclei (protons) fuse to form Helium-2, which immediately undergoes radioactive decay to "deuterium" ("heavy hydrogen" or hydrogen-2).

$$ {}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \longrightarrow {}^{2}_{2}\mathrm{He} \longrightarrow {}^{2}_{1}\mathrm{H} + \underbrace{{}^{0}_{+1}e^{+}}_{\text{positron}} + \underbrace{\nu}_{\text{neutrino}} $$

The positron (positive electron) will eventually meet an ordinary electron. They will then annihilate each other in a burst of gamma radiation.

More about neutrinos later.

Step 2:
The hydrogen-2 fuses with another proton forming helium-3, and gamma radiation.

$$ {}^{2}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \longrightarrow {}^{3}_{2}\mathrm{He} + \gamma $$

Step 3:
Two helium-3 nuclei fuse to form helium-4 & release 2 protons, which can re-cycle back to reaction 1.

$$ {}^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \longrightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} + \gamma $$

Overall: Hydrogen $\longrightarrow$ Helium + energy

$$ 4\,{}^{1}_{1}\mathrm{H} \longrightarrow {}^{4}_{2}\mathrm{He} + \text{energy} $$

Important Note:
If you are not familiar with the type of equations above, or are confused by "positrons" & "neutrinos", please continue on, then come back to this AFTER the later section on "Radioactivity".

The CNO Cycle (Carbon-Nitrogen-Oxygen)

This reaction cycle occurs in medium to large main sequence stars, and predominates in the larger ones. In a star the size of our Sun, both Proton-Proton and CNO Cycle reactions occur, although the P-P reaction is dominant.

In the reactions below, any nuclear "species" which occurs on both R&L of equations can be cacelled.

A cycle of reactions occurs as follows:

Fusion: $\cancel{{}^{12}_{6}\mathrm{C}} + {}^{1}_{1}\mathrm{H} \longrightarrow \cancel{{}^{13}_{7}\mathrm{N}} + \gamma$

Decay: $\cancel{{}^{13}_{7}\mathrm{N}} \longrightarrow \cancel{{}^{13}_{6}\mathrm{C}} + {}^{0}_{+1}e^{+} + \nu$

Fusion: $\cancel{{}^{13}_{6}\mathrm{C}} + {}^{1}_{1}\mathrm{H} \longrightarrow \cancel{{}^{14}_{7}\mathrm{N}} + \gamma$

Fusion: $\cancel{{}^{14}_{7}\mathrm{N}} + {}^{1}_{1}\mathrm{H} \longrightarrow \cancel{{}^{15}_{8}\mathrm{O}} + \gamma$

Decay: $\cancel{{}^{15}_{8}\mathrm{O}} \longrightarrow \cancel{{}^{15}_{7}\mathrm{N}} + {}^{0}_{+1}e^{+} + \nu$

Fusion: $\cancel{{}^{15}_{7}\mathrm{N}} + {}^{1}_{1}\mathrm{H} \longrightarrow \cancel{{}^{12}_{6}\mathrm{C}} + {}^{4}_{2}\mathrm{He} + \gamma$

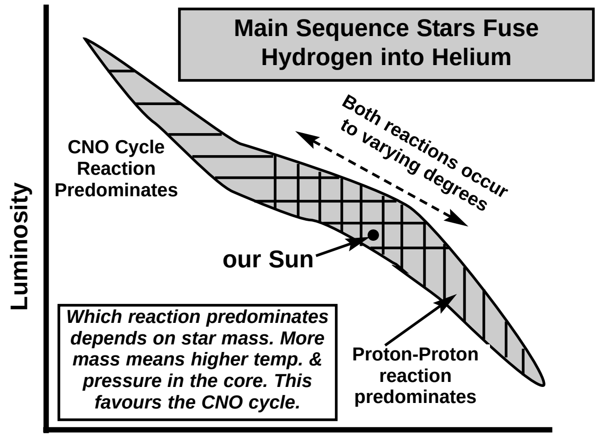
Overall, the result is the same as the P-P reaction:

$$ 4\,{}^{1}_{1}\mathrm{H} \longrightarrow {}^{4}_{2}\mathrm{He} + \text{energy} $$

Notice that carbon is involved in the first step, and is re-generated by the last step. It could be said that carbon acts as a <u>catalyst</u>.

As before, any positrons formed will soon meet an electron and be annihilated in a burst of gamma rays.

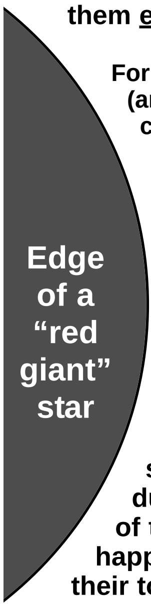
Both these main-sequence reactions involve fusion which (overall) converts hydrogen to helium. In each reaction a small amount of mass "disappears" and is converted to energy according to Einstein's $E = mc^2$ equation.



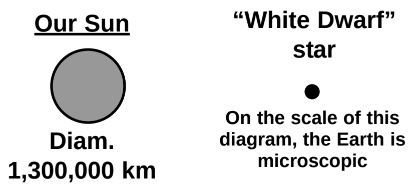
So, all main sequence stars turn hydrogen into helium via one or both of these fusion cycles.

Eventually, the core of the star becomes depleted in hydrogen and rich in helium. When a critical level is reached, the star enters a new phase of its life... we will get to that shortly.

When we introduced the H-R diagram, did you notice that we said "<u>MOST</u>" stars lie on the "Main Sequence"? This means that <u>some</u> stars have luminosity-temperature combinations that place them <u>elsewhere</u> on the H-R grid.



For example, "<u>Red Giant</u>" stars are very large, (and therefore luminosity is high) but relatively cool (therefore red in colour).
"<u>White Dwarfs</u>" are very small stars, (therefore luminosity is low) but they are relatively hot.



Astronomers have figured out that all stars go through a series of changes during their lives. Most stars spend most of their life on the Main Sequence, but what happens to them later depends very much on their total mass.

The various possibilities are described next.

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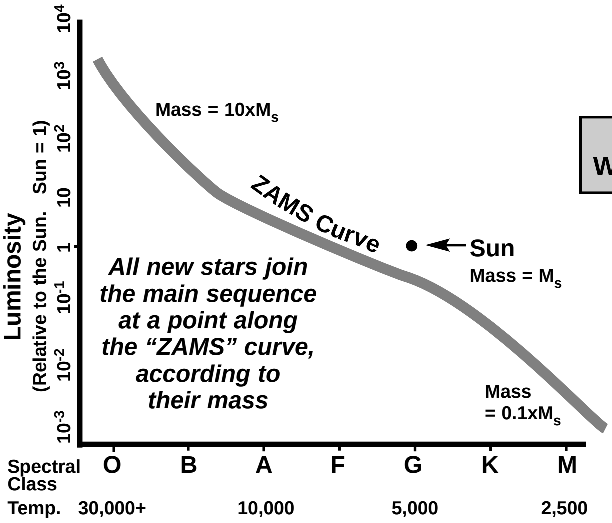
Stages in the Life of a Star

Every star begins its life on the "main sequence". If you plot the spectral class of a "newborn" star against luminosity, it lies very close to the lower border of the main sequence band on a H-R diagram. Since all new stars plot along this curve, it is called the "Zero Age Main Sequence" (ZAMS) curve.

Exactly where each new star joins the ZAMS curve depends entirely on its mass.

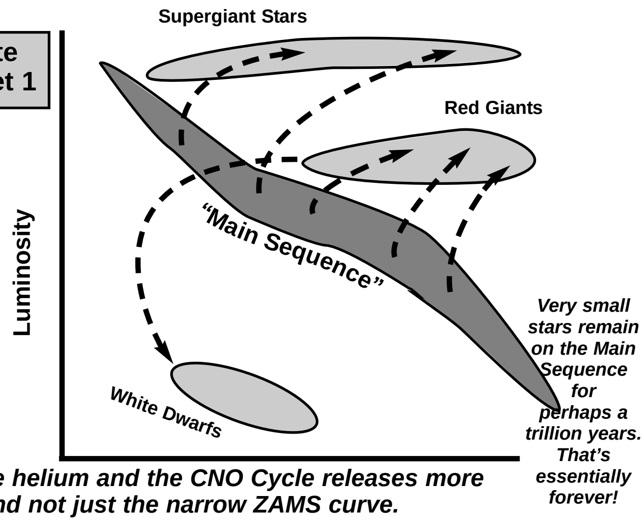


Small stars "burn" their fuel slowly and will stay on the main sequence for billions of years. A star the size of the Sun, for example, can be expected to remain on the main sequence for about 10 billion years. The Sun is currently about half-way through this chapter of its life.

The larger the star, the faster it burns its fuel and the shorter its life-time on the main sequence.

Eventually, every star reaches a stage when it leaves the main sequence, first expanding into a giant, then beginning the process of star death as a dwarf. The generalised pathways of a star's life are shown below.

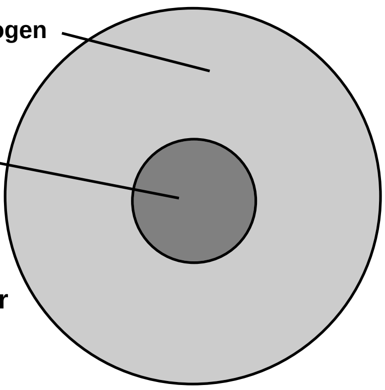
Complete Worksheet 1



All stars tend to get hotter & more luminous as they accumulate helium and the CNO Cycle releases more energy. That's why the Main Sequence is a thick band and not just the narrow ZAMS curve.

After the Main Sequence Phase

Large mass stars burn fast and hot; smaller stars burn slower and cooler, but eventually they all end up with a core depleted in hydrogen and rich in helium.

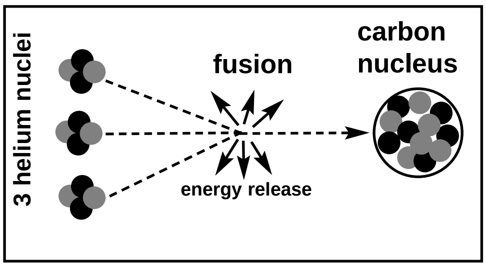


Up until now, the core of the star has not been hot enough for any other fusion reactions beyond the hydrogen to helium reactions.

Now, as it runs out of hydrogen, the core ceases producing energy and gravity causes it to collapse inwards. We're talking zillions of tonnes of collapsing matter which rapidly converts gravitational potential energy into heat.

The core temperature skyrockets and at a certain point a new fusion reaction begins... the core starts fusing helium into carbon.

$$3\,{}^{4}_{2}\text{He} \longrightarrow {}^{12}_{6}\text{C} + \text{energy}$$



When this happens, the extra heat generated in the core affects the layers of unreacted hydrogen surrounding the core. Depending on the size and density of the star, a "shell" of hydrogen may begin fusing around the outside of the core, adding even more heat, and possibly causing eruptions which may "blow away" outer layers of the star.

The main effect, however, is that the outer mantle of the star swells enormously with the extra heat coming from within. The star swells hugely to become a giant star.

Being so much bigger, it becomes much more luminous (moves upwards on the H-R diagram). At the same time, the outer surface actually becomes cooler, and its colour redder...

it has become a Red Giant star.

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Nucleosynthesis

Fusion in a giant star doesn't stop at carbon. Depending on the size and core temperature of the giant, a variety of fusions can occur, gradually producing nearly all the elements of the Periodic Table.

For example:

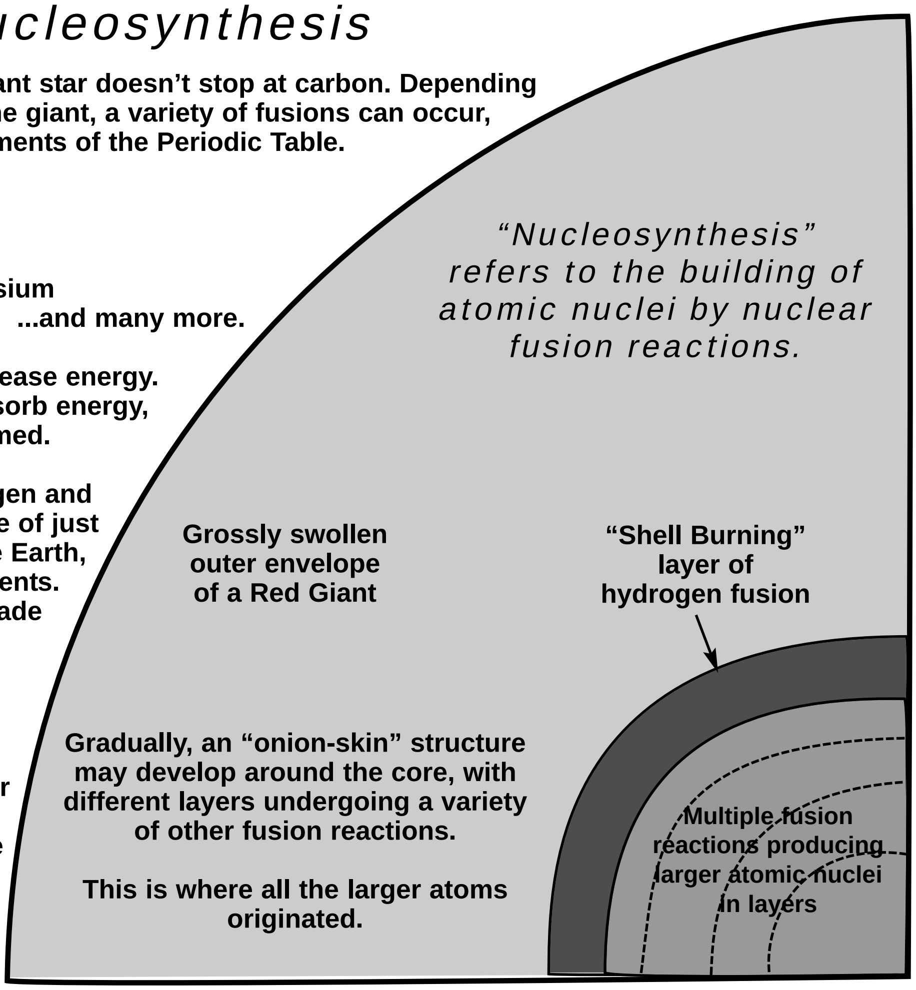
carbon + helium $\longrightarrow$ oxygen
oxygen + helium $\longrightarrow$ neon
oxygen + carbon $\longrightarrow$ silicon
neon + helium $\longrightarrow$ magnesium
magnesium + silicon $\longrightarrow$ iron ...and many more.

As far as iron, the fusion reactions release energy. Beyond iron, the reactions tend to absorb energy, but atoms as large as lead can be formed.

The universe began as entirely hydrogen and helium and is still predominantly made of just these two. In some places such as the Earth, however, there are many heavier elements. We believe that these have all been made by fusion in giant stars.

Eventually, the energy-producing fusions begin to run out of fuel. Remember that fusion to anything larger than iron, absorbs energy rather than releasing it. As iron accumulates in the core, the star's ability to release energy, reaches another critical stage...

... the star is about to die!



Star Death

Exactly what happens at the end of a star's life depends on its <u>mass</u>.

Small Stars Splutter & Fade

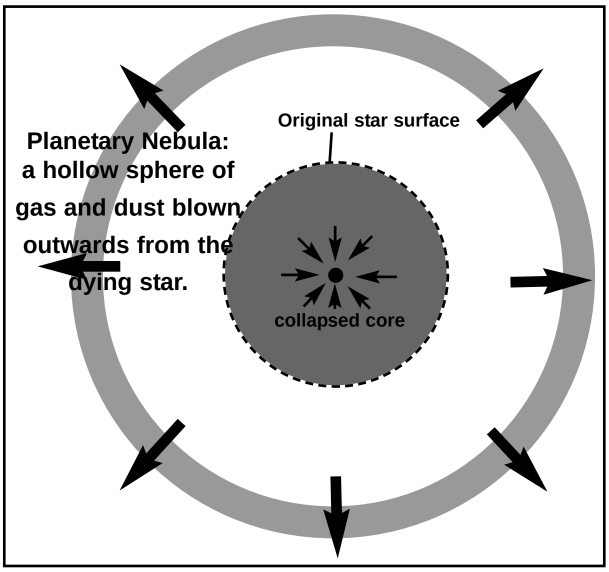
If the original mass of the star is less than about 5 times the mass of the Sun, the star goes through its "Red Giant" phase (previous page & above) starting by burning helium to carbon, and possibly developing an "onion-skin" structure of different fusion reactions in successive shells.

In a dying red giant there are sudden outbursts or "flashes" of energy as a shell runs out of fuel. Fusion slows dramatically. Energy production basically ceases. Gravity collapses matter inwards. This brings fresh fuel into the fusion zone which causes a sudden explosion, like throwing petrol onto a fire.

Such an explosion has the effect of blowing away an outer layer, as a hollow sphere of gas and dust called a "<u>planetary nebula</u>".

After several such events there may be little left of the star except its iron-rich core. Without any remaining "fuel" for fusion reactions, this core collapses under gravity to form a dense lump of "<u>degenerate matter</u>".

"Degenerate matter" is where the atoms themselves are compressed into a smaller volume by squashing the electron orbits closer to the atomic nuclei. A mass the size of the Sun can end up compressed down to the size of the Earth, and have a density of 1 tonne per cm^3.



Fusion has ceased, but this star remnant has a lot of residual heat, so its surface temperature may be around 10,000^{o}K. Being very small, the total luminosity is quite low.

On the H-R diagram, it plots to the left, but well below the main sequence. This is a "<u>White Dwarf</u>" star.

Over millions of years it radiates its residual heat, gradually cooling and disappearing from our view.

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Big Stars Go Out With a Bang

If the star's original mass is greater than about 5 times the mass of our Sun, its death is quite spectacular.

A star this large will certainly have developed an "onion-skin" layer structure with some heavy elements in the core. When this runs out of fusion fuel, the core suddenly collapses under gravity and rapidly implodes upon itself.

The outer layers suddenly have nothing holding them out there, so they fall inwards at an enormous speed. These outer layers still contain fusionable "fuel" which now ignites in a cataclysmic detonation which explodes & re-bounds outwards... a "Supernova" explosion.

Three significant things result immediately:

- **large amounts of heavy elements (up to and beyond uranium) are formed in a rapid burst of fusion events.**
- **the force of the explosion in a shell around the core, further accelerates the core implosion.**
- **the outer layers of the star are blown outwards in a fireball that briefly outshines a million stars, and continues expanding outwards as a cloud of debris for thousands of years.**

What becomes of the imploding core depends on its mass:

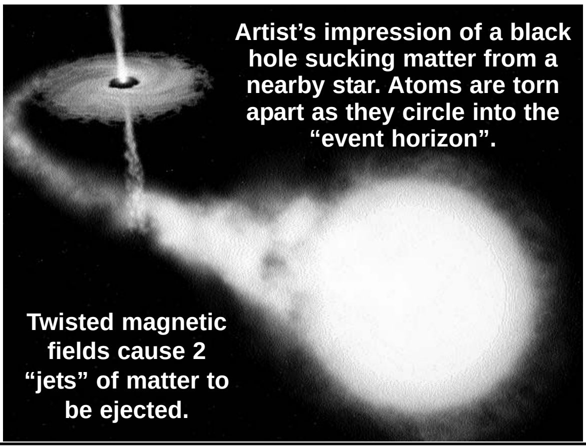
If the core is more than 1.4, but less than 3 solar masses, it forms a neutron star. The atoms are crushed together, so that electrons are forced into the nucleus of atoms, forming a solid ball of neutrons about 20 km across with a density millions of tonnes per cm^3.

The neutron star spins rapidly and gives out beams of high frequency EMR, such as X-rays. If the beam sweeps past the Earth we detect pulses of radiation. When first discovered, these were called "pulsars".

If the core is bigger than about 3 solar masses, nothing can stop the implosion.

The matter is crushed into a "singularity" with an intense gravitational field which not even light can escape from. Hence it is called a "black hole".

Inside the black hole we think that time stops and all the normal laws of physics no longer apply.



Artist's impression of a black hole sucking matter from a nearby star. Atoms are torn apart as they circle into the "event horizon".

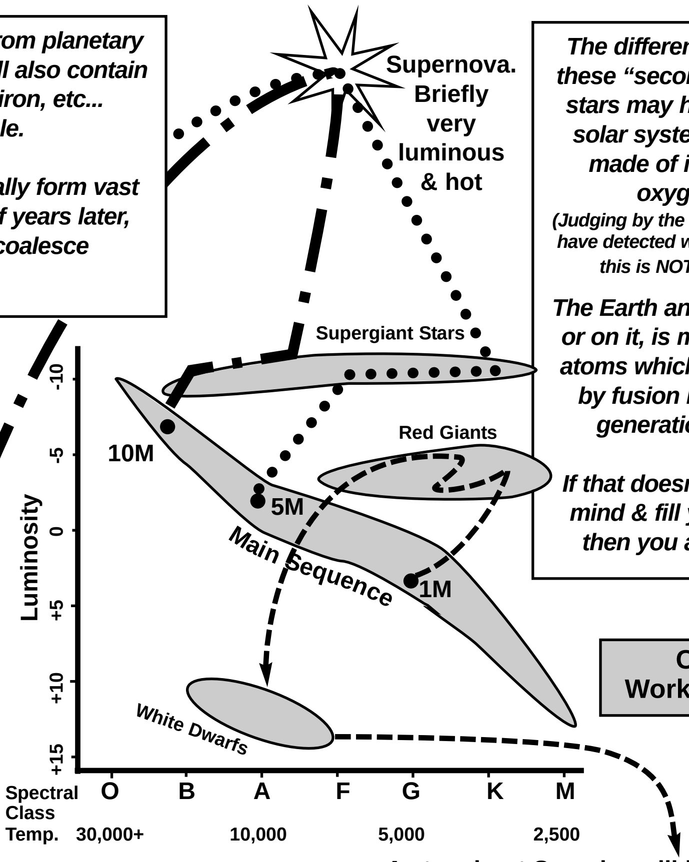
Twisted magnetic fields cause 2 "jets" of matter to be ejected.

H-R Pathways of a Star's Life

The debris blown away from a supernova or from planetary nebulas still contains a lot of hydrogen, but will also contain vast quantities of carbon, oxygen, silicon, iron, etc... all the elements of the Periodic Table.

Enormous quantities of such material eventually form vast clouds of interstellar gas and dust. Billions of years later, these clouds may begin to collapse and coalesce to form new stars...

The diagram shows the approximate life-pathways for a Sun-sized star, and one about 5 times more massive, and one 10 times more massive.



5M star leaves a core about 2M

Neutron Star & Pulsar. Hot, but very low luminosity. Radiations include UV & X-rays.

10M star leaves a core about 5M, which will collapse to form a BLACK HOLE. Zero Luminosity!

A star about Sun-size will become a Red-Giant, then a White Dwarf and finally "fade away" to a "Brown Dwarf".

The difference will be that these "second-generation" stars may have their own solar system of planets, made of iron, silicon, oxygen, etc.
(Judging by the number of stars we have detected which have planets, this is NOT uncommon.)

The Earth and everything in or on it, is mainly made of atoms which were created by fusion in a previous generation of stars!

If that doesn't boggle your mind & fill you with awe, then you aren't trying!

Complete Worksheets 2 & 3

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2. Structure of the Atom

For almost the entire 19th century, atoms were thought to be small solid particles which were NOT made of any smaller parts or pieces. This section of the module looks at the history of Science and how we came to have a very different understanding of atomic structure.

Cathode Rays

By the 1850's, scientists had developed the technology to produce quite high voltages of electricity and to make sealed glass tubes from which most of the air had been removed using a vacuum pump.

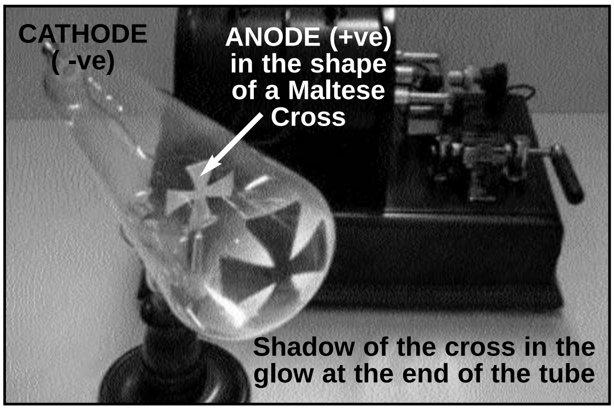
It wasn't long before these 2 things were combined, and some mysterious phenomena were discovered.

Of great interest were the glows & "discharges" in electrified vacuum tubes. They came from the negative electrode, or "cathode"... so these emissions were called "Cathode Rays".

Over the following 20 years these mysterious "rays" were studied by many scientists, most notably Sir William Crookes. He devised so many clever variations on these Cathode Ray Tubes (CRT's) that they were sometimes called "Crookes Tubes".

Experiments with CRT's

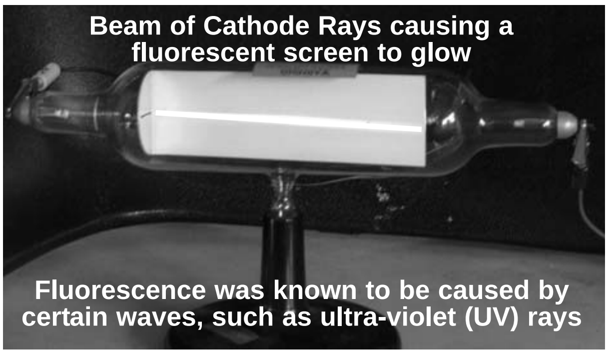
Maltese Cross Tube



This proves that Cathode Rays travel in straight lines from the Cathode.

Furthermore, Crookes tried this experiment with many different metals as his electrodes. The type of metal made no difference... Cathode Rays are identical, regardless of the materials used.

Tube With a Fluorescent Screen



Confusion About Cathode Rays

The evidence from these various experiments was very inconsistent... some of the features of cathode rays suggested they were particles, other results suggested they were waves.

Evidence that CR's were Waves

Cathode Rays:
- **Travel in straight lines like light waves.**
- **Cause fluorescence, like ultra-violet waves.**
- **Can "expose" photographic film, as light does.**

Evidence that CR's were Particles

Cathode Rays:
- **Carry kinetic energy and momentum, and therefore must have mass.**
- **Carry negative electric charge. (but this vital clue was missed for some time!)**

This confusion was finally settled by a famous experiment. In 1897, Sir Joseph John Thomson showed that cathode rays had both mass and negative charge.

He had discovered the electron.

The Model of the Atom

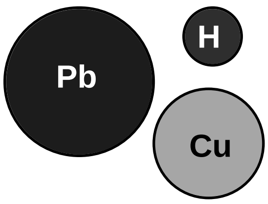
Before we look into Thomson's experiment, you are reminded of the prevailing theories about atoms at that time.

John Dalton (English, 1808) had experimented with chemical reactions and showed that substances always reacted and combined in fixed ratios by weight.

For this to happen, Dalton reasoned that each element must have unique atoms (of fixed weight) which could react and combine with each other in simple ratios.

He resurrected the "atomus" idea of the ancient Greek Democritus (400 BCE) and combined it with the new ideas of chemical elements & compounds.

Dalton's model proposed that atoms were unbreakable spheres, with no smaller parts. Each chemical element had different atoms with different weights and properties, so the atoms of lead are different to atoms of copper, etc.



This was the unquestioned model throughout most of the 19th century.

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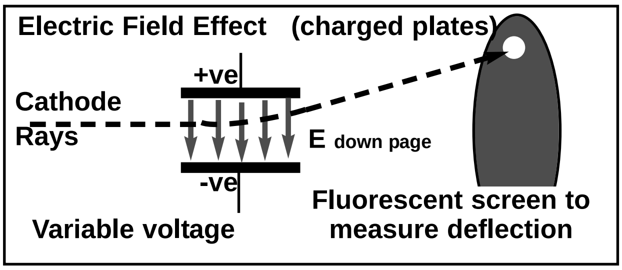
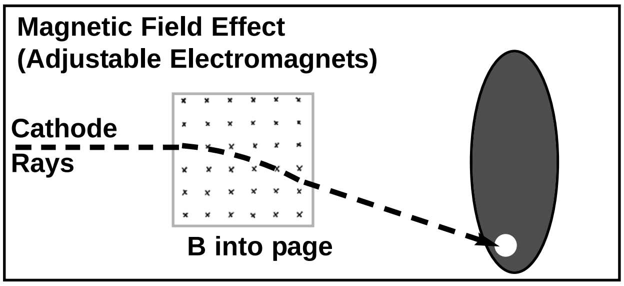
Discovery of the Electron... Thomson's Experiment

In 1897, the confusion and debate about Cathode rays was settled by one of the most famous, and critically important, experiments in the history of Science.

The British physicist J.J. Thomson set up an experiment in which cathode rays could be passed through both an electric field, and through a magnetic field, at the same time.





Thomson was able to adjust the strengths of the 2 fields so that their opposite effects exactly cancelled out, and the beam went straight through to the centre of the screen.

At this point, Force due to Electric Field = Force due to Magnetic Field

Since the strengths of the fields could be calculated from the currents and voltages applied to the plates and electromagnets, Thomson was able to calculate the ratio between the charge and mass of the cathode rays.

Charge to mass ratio = $\frac{Q}{m}$

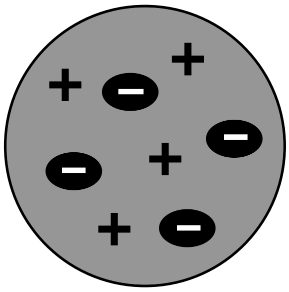
This established beyond doubt that cathode rays were particles (because they had mass) and were not waves.

Furthermore, he repeated the experiment with many different cathode materials and always got the same result. This meant that the exact same cathode ray particles were coming from every type of atom.

Other experimenters had already determined the charge-mass ratio for the hydrogen atom (the smallest atom). It was apparent that the cathode ray particle was much smaller than a hydrogen atom. The conclusion was that all atoms must be made of smaller parts, one of which was the "cathode ray particle", soon re-named ELECTRON.

A New Atomic Model

From this discovery, Thomson proposed a new model for the atom. It seemed that all atoms had smaller parts (the electrons) and since electrons carried a negative charge, but atoms overall are neutral, then atoms must also contain some positively charged material to balance the total charge.



Thomson suggested that atoms might consist of a positively charged "matrix" of matter with electrons embedded within it. This model quickly became known as the "Plum Pudding Model".

Finding the Charge of the Electron

Thomson had solved the mystery of the "cathode rays", discovered the electron and put forward a new model of the atom.

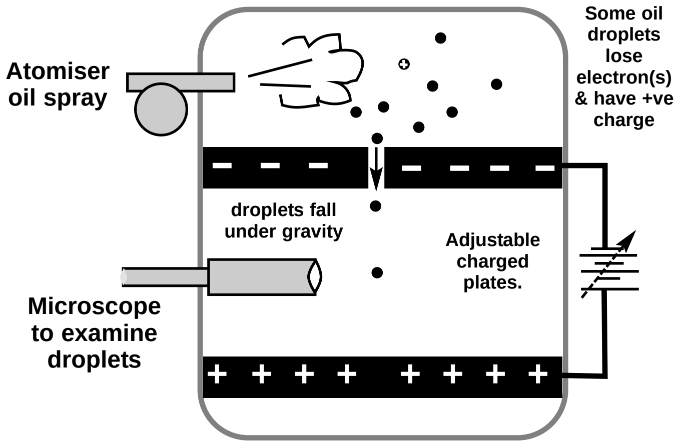
However, he had found a value for the charge-to-mass ratio (Q / m) so neither the electron's charge, nor mass were known... only the ratio between them.

In 1909 American physicist, Robert Millikan found a way to measure the electron's charge. The diagram shows schematically how this was done.

Tiny droplets of oil had their mass calculated from their known oil density and the terminal velocity they reached when falling through the air.

Some droplets developed a positive static electric charge from the sprayer. By adjusting the charged plates, a charged droplet could be held motionless when the forces on it were balanced:

Gravitational force = Electrical force



This equation could be solved to find the charge on the droplet. Millikan measured the charge on hundreds of droplets. There were many different charge values, but all were multiples of 1.6×10^{-19} C. He proposed that this was the charge of a single electron. Incidentally, this also showed that charge was quantised, thus fitting the (new) "quantum" idea.

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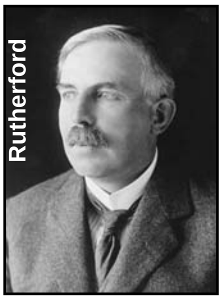
Radioactivity

In 1896, the French scientist <u>Henri Becquerel</u> accidentally discovered that certain minerals containing <u>uranium</u> were emitting a mysterious, invisible radiation. This was called "radioactivity".

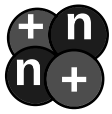
We will come back to cover this in detail later, but one of the scientists who became very interested was the New Zealander, <u>Ernest Rutherford</u>, who was a professor at Manchester University in England.



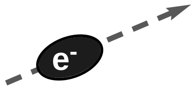
Rutherford had received the Nobel Prize in 1908 for his discoveries associated with radioactivity and had enlisted the help of the German physicist, <u>Hans Geiger</u>. Together they were developing methods of detecting, observing & counting radioactive radiations.

Rutherford had already discovered that there were 3 types of radiation and had named them. He didn't know the full detail we now have:

Alpha Radiation is a stream of particles. An alpha particle is a "chunk" of nucleus, made up of <u>2 protons and 2 neutrons</u>. It carries positive charge.



Beta Radiation is also a stream of particles: this time it is high-speed <u>electrons</u> ejected from an atomic nucleus. These carry negative charge.



Gamma Radiation is very high frequency <u>electromagnetic waves</u>, similar to X-rays, but carrying even more energy. They have no charge.

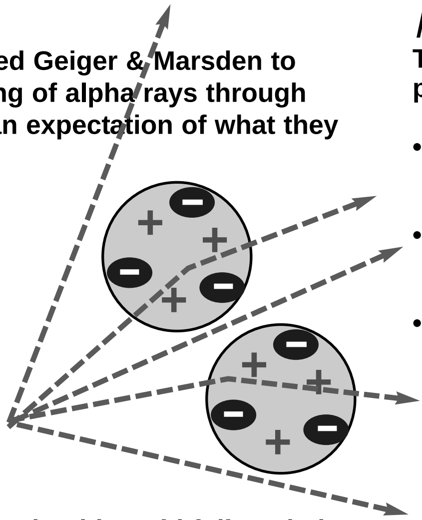
In 1909, Rutherford gave Geiger the task of measuring the deflection of alpha radiation as it passed through matter. Geiger carried out this experiment with his student <u>Ernest Marsden</u>.

The Geiger-Marsden Experiment

Expectations

When Rutherford directed Geiger & Marsden to investigate any scattering of alpha rays through matter, he already had an expectation of what they would probably find.

Based on Thomson's "Plum Pudding" model, it was predicted that most alpha radiation would pass straight through, with just a few being deflected through small angles.



The Results

Geiger & Marsden selected a thin gold foil as their "target" for the alpha rays because it could be made thin enough for the rays to pass through easily. (Alpha rays are not very penetrative.)

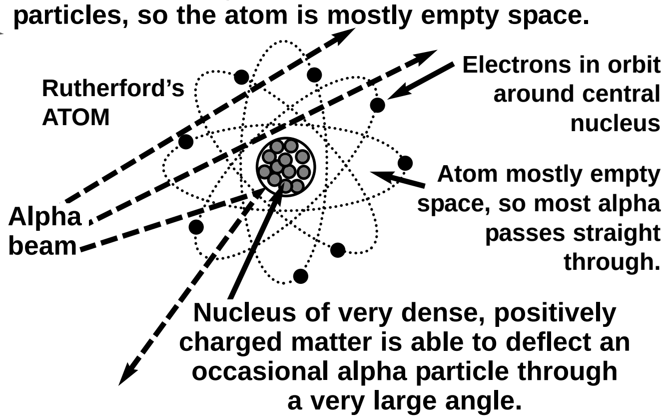
As expected, most of the radiation passed straight through. However, a few alpha particles were deflected through quite large angles and some even bounced back!

Rutherford later said that this was like firing an artillery shell at a tissue paper and have it bounce back to hit you... he was amazed by the result.

Rutherford's Explanation

To explain this unexpected result, Rutherford proposed a new model for the atom in 1911.

- At the centre is a tiny, dense nucleus with a positive electrical charge.
- The negatively charged electrons orbit around the nucleus.
- The distance from nucleus to the electron orbits is very large compared to the size of the particles, so the atom is mostly empty space.



Since negative charge was carried by particles (electrons) Rutherford thought it likely that the nucleus was made of positive particles. He later confirmed this (next page) and named these particles "protons".

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Confirmation of the Proton

In the second decade of the 20th century political events and WW1 caused a disruption & a slow-down in pure scientific research. Some promising young scientists died in battle and many others were drafted into weapons research.

There were, however, some exceptions:
Albert Einstein, a life-long pacifist, fled from Germany to Switzerland. He became a Swiss citizen and continued his work on General Relativity which he published in 1915.

Rutherford managed to continue his work as well.
In experiments conducted in 1917 (but not reported until 1919) he "fired" alpha radiation into nitrogen gas and recognised the "signature" of hydrogen atoms in his detectors.

He proposed that the "hydrogen" (a proton) must have been inside the nucleus of the nitrogen atoms and had been knocked out by the energy of the alpha collision.

$$^{14}_{7}N + ^{4}_{2}He \longrightarrow ^{17}_{8}O + ^{1}_{1}H$$

Nitrogen nucleus, Alpha particle, Oxygen nucleus, Hydrogen nucleus

Rutherford put forward the idea that the nucleus of a hydrogen atom is a single fundamental particle with a positive charge equal in magnitude to that of an electron.

All atomic nuclei, he argued, contain a number of these particles equal to the "Atomic Number" of the element and equal to the number of electrons in a neutral atom. At a conference in 1920, he proposed the word "proton" for these nuclear particles.

The mass of hydrogen atoms was already well known, so this defined the mass of the proton. However, the total mass of any atom (except hydrogen) was at least twice as much as the known mass of the protons plus electrons within it.

There must be more particles in the nucleus!

After this page, complete worksheets 4 & 5

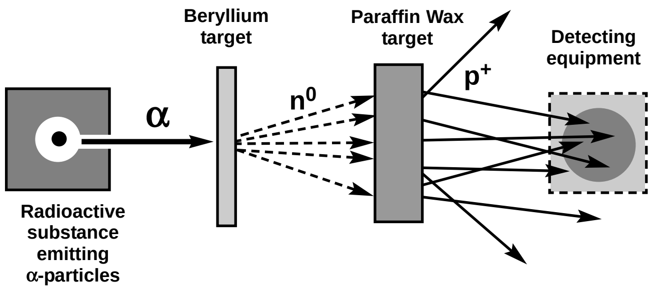
Discovery of the Neutron

By the 1920's it was known that there must be more to the atomic nucleus than just protons because the mass of atoms did not add up. One proposed solution was that there were extra protons combined with extra electrons in the nucleus.
This made sense, but the emerging science of Quantum Mechanics soon showed that the combination of (proton + electron) was impossible and violated the strange rules of the new Physics.
Back to the drawing board... we are looking for another particle!

Experiments in Germany in 1931 had revealed a mysterious new radiation which had been assumed to be gamma rays. Rutherford was not convinced. Neither was James Chadwick at Cambridge University. In 1932, he repeated the German experiments with a view to looking for the "missing" atomic particle, already called a "neutron".

It was impossible then to detect and measure such a particle directly. The method Chadwick used relied upon neutrons colliding with other particles, then applying the scientific principles of Conservation of Energy and Conservation of Momentum to measure the properties of the neutron.

The diagram shows schematically the experiment.



• The alpha (α) particles emitted by a radioactive substance were used to bombard a beryllium target.

• The beryllium emitted neutrons, which (having no electrical charge) are very penetrating and are unaffected by electric or magnetic fields, so could not be measured or studied directly. The German scientists had thought the radiation was gamma (γ) waves of extreme high energy.

• Some of the neutrons then hit a second target of paraffin wax, which has a lot of hydrogen in it. Occasionally a neutron collision would dislodge a proton.

• Chadwick was able to study some of these protons and measure the energy they carried.

• Chadwick could then apply the principles of Conservation of Momentum and Energy to calculate the mass and velocity of whatever had hit the protons and dislodged them.

The results indicated the presence of a particle (not γ-rays) with a mass almost the same as a proton, and no electric charge. This matched perfectly with the (then hypothetical) neutron, so the existence of the "missing" nuclear particle was confirmed.

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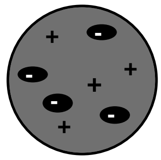
3. Quantum Mechanical Nature of the Atom

What Has Gone Before...

The entire Science of Chemistry and much of Physics is built on the foundation of Atomic Theory... the concept that all matter is composed of atoms. Initially conceived as tiny, unbreakable particles of matter, by the beginning of the 20th century it became apparent that the atom was composed of smaller parts.

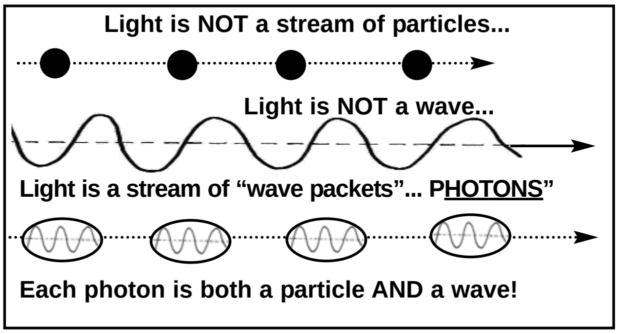


In his famous experiment with cathode rays, J.J.Thomson had discovered the (negatively charged) electrons in all atoms.

This meant that there also had to be a positive part of each atom.

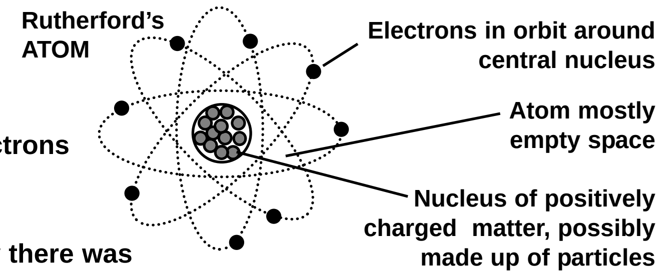
In 1900, Max Planck had proposed the Quantum Theory to explain the details of the "Black Body Radiation Curves".

In 1905, Einstein then explained the strange phenomenon of the Photoelectric Effect by using Planck's quantum idea. He proposed that light is not just a wave, nor a stream of particles, but made up of "wave packets". Einstein also proposed his "Theory of Relativity" in 1905. Classical Physics was being turned upside-down by this sequence of new, fundamental discoveries.



Rutherford Model of the Atom

In 1911, Ernest Rutherford explained the unexpected results of the Geiger-Marsden experiment.
He proposed that the positively charged part of an atom must be concentrated into a tiny "nucleus", with the electrons orbiting around it.



Problems with Rutherford's Atom

Even as he proposed his atomic model, Rutherford knew there was a huge problem with it.

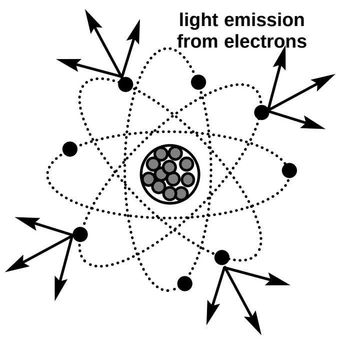
The existing theory of Electromagnetic Radiation (EMR) contained the concept that if an electrically charged particle was accelerating, then it must emit EMR, in the form of light waves.

Since Rutherford's electrons were imagined to be in circular orbits around the nucleus, and since circular motion involves constant (centripital) acceleration, then it follows that each electron should be constantly emitting light. Trouble is... they obviously don't!

Existing accepted theory required that an orbiting electron should emit light energy continuously.

Obviously they don't, or all substances would constantly glow with light.

However, atoms DO emit light if stimulated with energy, such as in a high-voltage discharge tube.



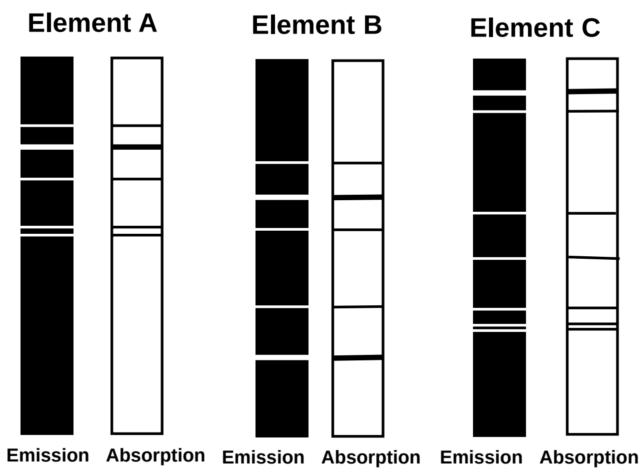
Spectral Lines

You are reminded of emission & absorption spectra and how each element has its own "fingerprint" of spectral lines.

These were studied extensively in the 19th century and by the time of Rutherford they were already being used by astronomers to classify stars (the "spectral classes" in the Hertzsprung-Russell diagram) and to identify the elements within a star.

However, there was just one little problem, which was a bit embarrassing...

No-one had the faintest idea how to explain them!



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The Balmer Series & Rhydberg Equation

The lines in the emission spectrum of hydrogen had been discovered many years before Rutherford's work, and were known as the "Balmer Series".

Each line was given a name (H_α, H_β, H_χ & H_δ) and the precise wavelength of each had been measured. Other similar series of lines were known to exist in the invisible infra-red and ultra violet parts of the EMR spectrum.

No-one could explain them, but mathematicians Balmer and (later) Rhydberg had worked out that the exact wavelengths of the hydrogen spectrum lines could be calculated from an empirical equation:

The Rhydberg Equation

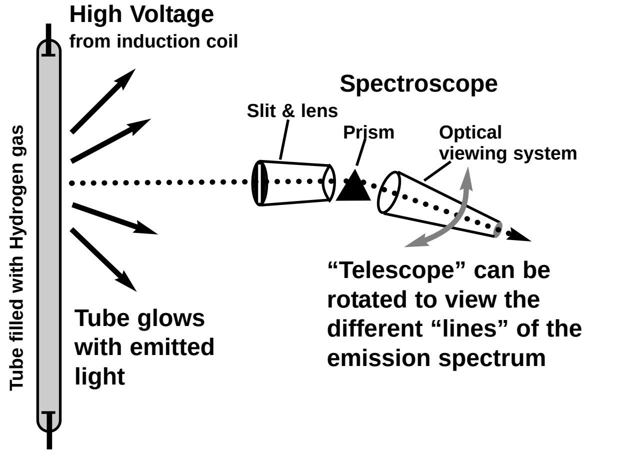
$$\frac{1}{\lambda} = R_H\left(1/n_f^2 - 1/n_i^2 \right)$$

λ = wavelength of the spectral line (metres)
R_H = the "Rhydberg constant" = 1.097×10^7
n_f = an integer number.
For the Balmer series $n_f = 2$
n_i = an integer number.
To calculate the wavelengths of the 4 lines of the Balmer series, n_i takes the values 3, 4, 5, 6.

Practical Work

Emission Spectrum of Hydrogen

You may have observed the emission spectrum for hydrogen by using a spectrometer to view the light from a discharge tube filled with low-pressure hydrogen gas.



You will have seen that the light from a hydrogen discharge tube is composed of 4 visible bright lines of light. These are the "Balmer Series". (left)

Each line is one single wavelength of light.

The fact that the Rhydberg equation worked was strong evidence that there was an underlying "law" controlling the hydrogen spectral lines. The fact that a series of integer numbers were involved was a clue that connected the whole thing to Plank's Quantum Theory...

Planck's Quantum Theory

A quick revision of what you learned in Module 7...

In 1900, Max Planck proposed a radical new theory to explain the black body radiation. He found that the only way to explain the exact details coming from the experiments, was that the energy was quantised: emitted or absorbed in "little packets" called "quanta" (singular "quantum").

Planck proposed that the amount of energy carried by a "quantum" of light is related to the frequency of the light and can be calculated as follows:

$$E = h.f$$

E = energy of a quantum, in joules (J)
h = "Planck's constant", value 6.63×10^{-34}
f = frequency of the wave, in hertz (Hz)

You are reminded also, of the wave equation:

$v = \lambda.f$ (or, for light) $c = \lambda.f$ so $f = c / \lambda$.

Combined with Planck's equation, this gives an additional relationship:

$$E = h.c / \lambda$$

Example Calculation

a) Use the Rhydberg Equation to find the wavelength of the H_δ line of the hydrogen spectrum, given that $n_f = 2$ and $n_i = 6$.

$$\frac{1}{\lambda} = R_H\left(1/n_f^2 - 1/n_i^2 \right)$$
$$= 1.097 \times 10^7 \left(1/2^2 - 1/6^2 \right)$$
$$1/\lambda = 2.438 \times 10^6$$
$$\therefore \lambda = 4.10 \times 10^{-7}\ \text{m} \quad \text{(410 nanometres)}$$

b) Calculate the energy carried by one photon of light in the H_δ spectral line.

$$E = h.c / \lambda$$
$$= 6.63 \times 10^{-34} \times 3.00 \times 10^8 / 4.10 \times 10^{-7}$$
$$= 4.85 \times 10^{-19}\ \text{J.}$$

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Neils Bohr Puts It Together

It was the Danish physicist Niels Bohr (1885-1962) who put these separate threads together in 1913. He used Plank's Quantum Theory to modify the Rutherford model of the atom in such a way that:

- **the problem of radiation that should be emitted constantly from accelerating electrons (in Rutherford's atomic model) was overcome.**
- **the reasons for emission spectra were explained.**
- **the empirical nature of the Rhydberg Equation was given theoretical backing and mathematical validity.**
- **the reasons for the "valency" of different atoms & how & why they combine in fixed ratios became clear.**

(The last point is fundamental to Chemistry and understanding chemical bonding and formulas. It will not be pursued any further in this topic.)

Bohr's Postulates

Electrons orbit only in "allowed" orbits.

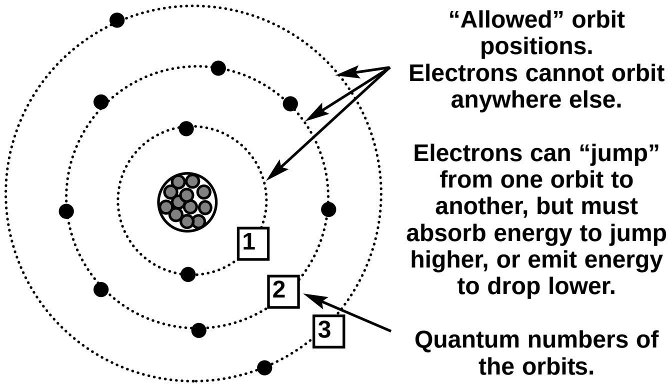
Bohr theorised that there are a series of orbits, at fixed distances from the nucleus, in which an electron will not constantly emit radiation as demanded by classical theory. **(Why is explained later.)**

Electrons gain or lose energy to "jump" orbits.

To jump up to a higher orbit, an electron must gain a certain quantity of energy. If it drops back to lower orbit, it must emit that exact same amount of energy.

These quantities of energy are "quantised", so each orbit is really a "quantum energy level" within the atom.

The amount of energy absorbed or emitted during a "jump" is defined by Plank's Equation E = hf, and the corresponding wavelengths of light are defined by the Rhydberg Equation. The integer numbers n_f and n_i turn out to be the "quantum numbers" of the orbits, counting outwards from the nucleus.



Electrons in "allowed orbits" have quantised amounts of angular momentum.

Bohr figured out that the amount of angular momentum possessed by an electron must always be a multiple of $h/2\pi$.

The significance of this comes later.

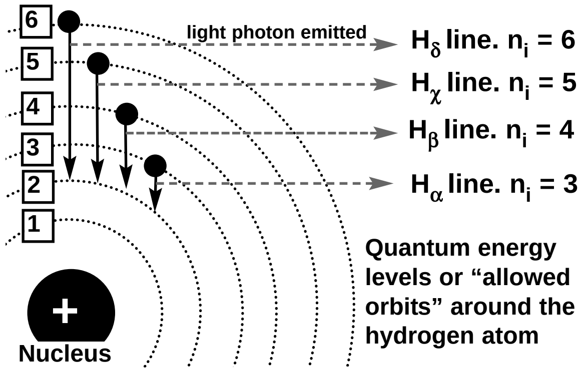
Bohr & the Balmer Series

Let's see how Bohr's ideas work with regard to the Balmer Series of hydrogen emission lines.

Bohr suggested that the H_α emission line was due to an electron dropping from the 3rd orbit down to the 2nd orbit. It must lose a precise quantum of energy, so it emits a photon of light at a precise frequency given by E = hf.

In the Rhydberg Equation, $n_i = 3$ and $n_f = 2$. The calculated wavelength (λ) agrees perfectly with the observed spectral line. Plank's Quantum Equation calculates the energy of that photon of light.

Bohr argued that this amount of energy must represent the difference in energy level from orbit 2 to orbit 3.



The other lines of the Balmer Series represent electrons dropping from higher orbits to the 2nd orbit:

H_α line. $n_i = 3$	**$n_f = 2$ in each case**	**Increasing energy difference gives higher frequency (and shorter wavelength) of spectral light**
H_β line. $n_i = 4$		
H_χ line. $n_i = 5$		
H_δ line. $n_i = 6$		

It all worked!
Bohr's idea gave a theoretical explanation for the Rhydberg Equation, which had been empirically derived to explain the observed spectral lines.

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Limitations of the Rutherford-Bohr Model

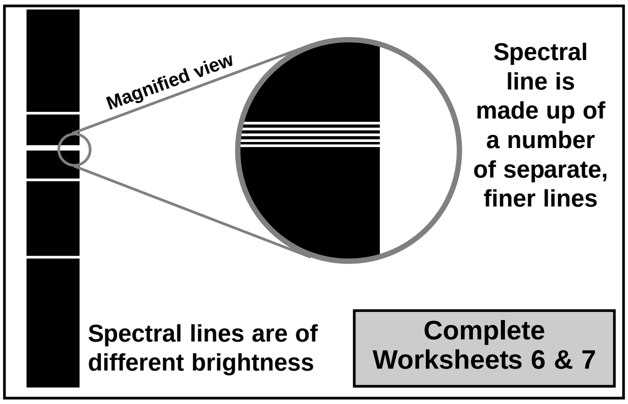
Despite the way that Bohr's Postulates seem to solve the problem with Rutherford's brilliant new concept of the atom, there were still unexplained difficulties.

Bohr Model worked only for Hydrogen
Hydrogen is the simplest atom, with only one electron and one proton.

Attempts to apply the model to larger atoms failed, because multiple, orbiting electrons interact with each other as well as the nucleus, and the Maths becomes too complex to solve all the simultaneous equations.

Different Intensities of Spectral Lines
The different spectral lines showed different intensities or brightness. This means that some orbital "jumps" by electrons always occur more often than others. Bohr's model had no explanation as to why.

"Hyperfine" Spectral Lines
When the spectral lines were examined more closely, most were found to be made up of a number of very fine lines close together. *(Chemistry students may relate this to "Orbital Theory")*



The Zeeman Effect
When a discharge tube is operated within a magnetic field, each spectral line is split up into several separate lines.

This, and the presence of the "hyperfine lines", suggested that the energy levels or orbits were divided into a number of "sub-orbits" of slightly different energy. Bohr's model had no explanation for this.

Like all scientific models, the Rutherford-Bohr atom is a human attempt to explain the observed facts of nature. In its day, this model was the best explanation available, but it was recognised that certain facts remained unexplained.

This doesn't make the model wrong... simply incomplete. It was a "work-in-progress", to be added to and refined by later scientists. This is the way Science works. If further evidence had proven it totally wrong (as can happen) you would not be studying it!

You might notice that the Rutherford-Bohr model of the atom is still used to explain basic Chemistry to students in high schools today, over 100 years after it was developed.

De Broglie's Matter Waves

Remember that in 1905 Einstein had explained the Photoelectric Effect by suggesting that light has both wave and particle properties. (For this he was awarded the Nobel Prize)

Light is a stream of "wave packets"... "PHOTONS"

Each photon is both a particle AND a wave!

Einstein had used Planck's Quantum Theory to explain a phenomenon that "classical" Physics was unable to explain.

In 1924, a young graduate student Louis de Broglie (French, 1892-1987) turned this concept around...

If light waves can have particle-like properties, does this mean particles can have wave-like properties?

Using Quantum Theory and Bohr's atomic model, de Broglie developed a mathematical model for an electron in orbit around the nucleus acting as a particle with wave properties.

You can derive the de Broglie equation from Einstein, Planck & the wave equation:

$$E = mc^2 \qquad E = h.f \qquad c = \lambda.f$$

$$mc.c = h.f \qquad \text{so} \qquad mc.\lambda.f = h.f$$

$$\therefore \; mc.\lambda = h$$

(and "c" is a velocity, so this can be re-written as...)

$$\lambda = h / mv$$

Now "mv" is momentum, so this equation links to Bohr's postulate about electrons having quantised angular momentum in their "allowed" orbits.

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

λ = wavelength (metres) of the electron.
h = Planck's constant (= 6.63×10^{-34})
m = mass of the electron (= 9.11×10^{-31} kg)
v = velocity of the electron, in ms^{-1}.

Example Calculation
Find the wavelength of an electron which is travelling at a velocity of 4.35×10^5 ms^{-1}.

Solution

$$\lambda = \frac{h}{mv} = 6.63 \times 10^{-34} / (9.11 \times 10^{-31} \times 4.35 \times 10^5)$$

$$= 1.67 \times 10^{-9} \text{ m} \qquad (1.67 \text{ nanometres})$$

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De Broglie's Matter Waves *(cont.)*

Impact of de Broglie's Hypothesis

De Broglie's proposals had almost no impact on the scientific community at first. His mathematics were checked and found to be totally correct. His hypothesis was totally consistent with the Quantum Theory, and with the Bohr model.

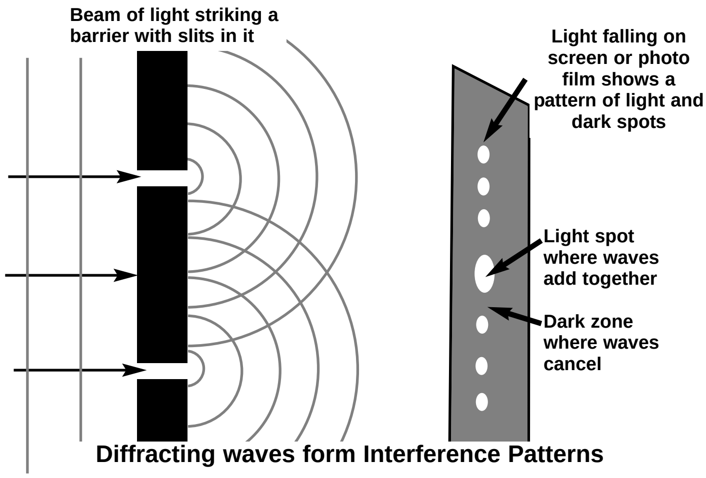
The physicists of the day, including Planck, Einstein, Rutherford and Bohr were all very interested by his work, but it was just a neat mathematical exercise, without any evidence based in experiment or observation.

Usually, scientists observe a phenomenon and then try to explain it by theory. de Broglie was putting theory first, without any facts to explain!

Eventually, (as happens in Science) an experiment was done to test the hypothesis.

Diffraction & Interference

You are reminded (from Module 7) of the interference patterns which arise from the diffraction of light.



Diffracting waves form Interference Patterns

How do you tell if something is a wave or not?
Simple: test electrons to see if they show diffraction & interference patterns!

Davisson & Germer's Experiment

Between 1925-7, American physicists <u>Davisson and Germer</u> used a modified cathode ray tube to test de Broglie's hypothesis.

A beam of electrons travelling through a vacuum was allowed to strike a crystal of nickel, specially prepared so that electrons would reflect from parts of it. Different parts of the beam could then overlap their pathways as they travelled into a detection device, which could measure the intensity of the beam at varying positions.

Result?

<u>An interference pattern was detected</u>!

This proved that electrons have wave properties, and confirmed the de Broglie hypothesis.

Why Are Bohr's "Allowed" Orbits Stable?

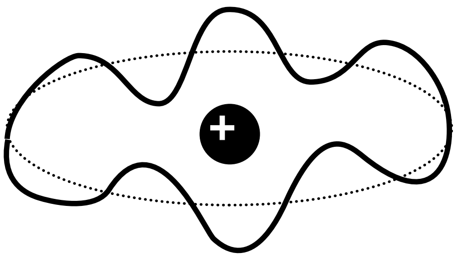
A quick review of some important points:

Rutherford's atomic model places electrons in orbit, but classical theory predicts they should constantly be emitting light, because they are accelerating.

However, this isn't happening, so Bohr proposes that there are "allowed", stable orbits where electrons don't constantly give off light. (They only radiate when they "jump" orbits)

What makes these "allowed orbits" stable?
de Broglie's particle-wave theory of the electron explains:

An allowed orbit is where the <u>wavelength</u> of the electron exactly fits to form a "standing wave" around the nucleus.



An electron forms a "Standing Wave" around the nucleus

"Standing waves" are a well-known wave phenomenon in which an exact number of full wavelengths can "resonate" or reverberate in a stable way. For example, all musical instruments involve standing waves of sound energy in a string or air space. ***(Revise these ideas in module 3)***

The "allowed orbits" around an atom are located at distances from the nucleus which allow the quantum energy of the electron to fit in an exact number of wavelengths to form a standing wave.

At any other distance, the orbit cannot fit a standing wave with an exact number of wavelengths, so the electron <u>cannot exist there</u>.

The electron is a <u>particle</u>, with mass and momentum. It is also a <u>wave</u>, with a wavelength ($\lambda = h/mv$) and capable of diffraction, interference and standing wave behaviour.

<u>Welcome to the world of Quantum Physics!</u>

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Quantum Mechanics

At this point the Syllabus requires that you analyse the contribution of one particular scientist to our modern understanding of the atom. We think that's a bit unfair.

In the 1920's, Quantum Theory was being accepted as a "necessary evil" to satisfactorily describe the structure of an atom, and account for all the known observations. However, the explanations being used were a mixture of new "quantum" ideas overlaid on a framework of "classical" Physics, so it was all rather artificial or contrived.

It was the theoretical work of many great scientists that turned "Quantum Theory" into "Quantum Mechanics"; a complete, new branch of Physics without the need for any reference to the "old" Physics.

Although the details of their work are beyond the scope of this course, we have chosen 3 of the best:

Werner Heisenberg

(German, 1901-76) is best remembered for the "Heisenberg Uncertainty Principle", for which he was awarded the Nobel Prize in 1932.

Heisenberg developed the mathematical framework for Quantum Mechanics. He showed that the dual nature of the "particle-wave" which describes the electron (and the light photon), makes it impossible to know everything about any particle at any moment. Either you know where it is, or you know how much momentum it has, but you cannot know both things at once with any certainty.

This "uncertainty" about things at the atomic scale was described by Heisenberg as mathematical probabilities. Thus, an electron orbit becomes a "region of probability" in which there is a good chance (but not a certainty) that the electron exists as either particle, or standing wave.

Wolfgang Pauli

(1900-58) was born in Austria, but became an American citizen. He is best remembered for the "Pauli Exclusion Principle", (Nobel Prize 1945) which states that 2 electrons in the same atom cannot have exactly the same quantum state.

His mathematical analysis established the idea that the Bohr-de Broglie orbits are just one of several different types of quantum properties that electrons can have.

This gives rise to the idea of "sub-orbits" within an atom (this explains the "hyperfine lines" in emission spectra) and shows why 2 electrons with almost the same quantum state, but opposite "spin", will tend to pair up. (e.g. electron pairs in chemical bonding.)

He made important contributions to understanding nuclear processes as well.

Complete Worksheets 8 & 9

Erwin Schrodinger (Austrian, 1887-1961)

Schrodinger is known as the "father of Quantum Mechanics". His mathematical "wave function" equation became the basis for understanding many aspects of the sub-atomic world and now under-pins much of modern Physics & Chemistry.

Erwin Schrodinger in 1933

All previous "quantum equations" grew from Planck's work plus that of Einstein & classical Physics. In contrast, Schrodinger's "wave function" is a complex mathematical description of a system totally built from quantum energy effects.

Schrodinger's equations do not rely on any aspects of "classical Physics", but stand alone in their own right. For this work, he was awarded the Nobel Prize in 1933.

Schrodinger was unsettled by some of the implications & interpretations of Quantum Mechanics. While fully supportive of its statistical aspects (eg Uncertainty Principle) he was sceptical about implications such as "quantum superposition" ("entanglement"). To learn more, research his famous paradox known as "Schrodinger's Cat".

When studying Quantum Physics, you should bear in mind a statement attributed to another great scientist, Richard Feynman, who said:

"If you think you understand Quantum Mechanics, then you don't understand Quantum Mechanics!"

(In fact, it may be an urban myth that he ever said this... but, if he didn't say it, he should have!)

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4. Properties of the Nucleus

Things to Know About the Nucleus

Nucleons
A "nucleon" means any particle located in the nucleus of an atom. There are 2 types of nucleon:

Protons
The existence of protons was considered likely almost as soon as the electron was discovered. By the 1920's the proton had been positively identified, and its properties measured.

Neutrons
As early as 1907 it had been suggested that protons alone were not sufficient to account for the mass of most atoms. It was suspected that there must be another nucleon, with considerable mass, but no electric charge. However, it was 25 years before the neutron's existence was proven.

Nucleon Number
The sum of the (protons + neutrons) in a particular nucleus is called the "nucleon number". It must be a whole number.

Compare this to the "atomic mass number". These terms are inter-changeable.

Properties of Nucleons

	Proton	Neutron
Electrical Charge	$+1.602\times10^{-19}$C	0 (neutral)
Mass	1.673×10^{-27}kg	1.675×10^{-27}kg

Note that:
• The charge on a proton is exactly the same magnitude, but of opposite sign to that carried by an electron.

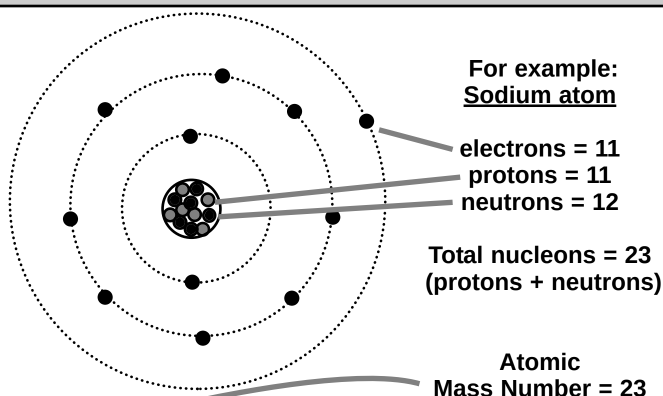
• So, in a neutral atom:
protons = electrons = "Atomic Number"

• Protons and neutrons have almost identical masses. (The neutron is slightly heavier)

Both are almost 2,000 times heavier than an electron, so virtually all the mass of an atom is in the nucleus.

protons + neutrons = "Atomic Mass Number"

Thus we get the familiar atomic model, with electrons (in Bohr's allowed orbits) around a nucleus of protons and neutrons.
MAKE SURE YOU UNDERSTAND THE SHORTHAND DESCRIPTION



$^{23}_{11}$Na

What Holds the Nucleus Together?

This question had been asked as soon as Rutherford had proposed that atoms have a nucleus. There were just 2 forces then understood, which could be operating in the nucleus:

Gravity
All masses attract all other masses by gravity. This would attract all nucleons to each other.

Electrostatic Forces
All charged particles exert a force on other charged particles. This force would not act on neutrons, but should cause protons to be repelled by other protons.

Calculations showed that the electrostatic repulsion would be much, much stronger than gravity. The nucleus should instantly fly apart!

Since the nucleus does exist, and doesn't instantly explode, it was realised that there must be another force operating. It was called simply the *"Strong Nuclear Force"*.

Its properties could be inferred and calculated:
• It must be much stronger than the proton-proton electrostatic repulsion.

• It must be independent of charge and attract all nucleons... protons & neutrons.

• It must be extremely short-ranged, operating only across the tiny distances of the nucleus.
(Otherwise it might cause neighbouring atomic nuclei to fuse together & eventually pull all matter into one lump!)

Even before its existence was proven, the Strong Nuclear Force was known to exist, and scientists began speculating on how to tap into its enormous energy potential...

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Reading the Periodic Table

How to Read the Information for Each Element

13
Aluminium
Al
26.98

"Atomic Number" ***(= protons = electrons)***
The elements are numbered, in order, across and then down the table. This puts the elements in a numerical order, but it also tells you how many electrons & protons in each atom.

Name of the Element

Chemical Symbol
Each element has a short-hand symbol. It is always one capital letter, OR if 2 letters, always a capital followed by a lower case letter.

Shorthand for an Atom

From this, you can work out that each Argon atom contains 18 electrons, 18 protons and 22 neutrons.

$^{40}_{18}\mathrm{Ar}$

Mass No. above
Chemical symbol
Atomic No. below

"Relative Atomic Mass" (RAM) **(Sometimes loosely called the "Atomic Weight")**
This gives the relative mass of an "average" atom of the element.

Whoa! Wait a minute! That cannot be correct!
The Atomic Mass Number (Nucleon Number) must be a whole number. What's going on?

The explanation lies in a knowledge of *ISOTOPES...*

Isotopes

You know that the atoms of an element are all the same as each other. **<u>Actually, that's not quite true</u>!**

All the atoms of an element have exactly the same
- **number of protons &**
- **number of electrons**

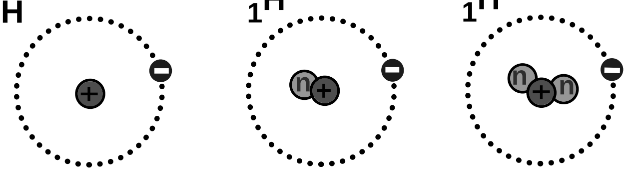
} = "Atomic Number"

It is the number of electrons which gives each atom its chemical properties, and defines it as a particular element. However, the number of neutrons can vary.

For example, hydrogen has the smallest, simplest atoms of all, but there are 3 variations, or "isotopes".

Example: Isotopes of Hydrogen

$^{1}_{1}\mathrm{H}$ $^{2}_{1}\mathrm{H}$ $^{3}_{1}\mathrm{H}$



0 neutrons **1 neutron** **2 neutrons**

These atoms have the same chemistry, because the electrons are the same ; they are all Hydrogen.

However, their Mass Numbers are different.

> **ISOTOPES are atoms of the same element (same Atomic Number) but with different numbers of neutrons and different ATOMIC MASS NUMBERS. Their chemistry is the same.**

Most elements exist in nature as a mixture of 2 or more isotopes. The "<u>Relative Atomic Mass</u>" shown on the Periodic Table is the <u>average</u> of the mixture of isotopes that occurs on Earth.

Example: Chlorine has 2 main isotopes

$^{35}_{17}\mathrm{Cl}$	$^{37}_{17}\mathrm{Cl}$
17 protons	**17 protons**
17 electrons	**17 electrons**
<u>18 neutrons</u>	**<u>20 neutrons</u>**

On Earth, there is a mixture of these 2 isotopes in such a proportion so that the "weighted average" atomic mass is 35.45. This is the value of R.A.M. shown in the Periodic Table.

Isotopes are commonly described by their individual mass numbers. The isotopes above are "Chlorine-35" & "Chlorine-37", or simply Cl-35 & Cl-37.

The isotopes of Hydrogen (at left) are Hydrogen-1, Hydrogen-2 and Hydrogen-3.
(These actually have "special" names: H-2 = "deuterium", H-3 = "tritium".

Calculating R.A.M. from Isotope Data

If you know the proportions of each isotope in a sample of an element, you can easily calculate the R.A.M.

<u>Example</u>: A sample of chlorine is found to contain 77% Cl-35 and 23% Cl-37.

R.A.M. = (nucleon no. x %) + (nucleon no. x %) +... for each isotope

$$= 35 \times \frac{77}{100} + 37 \times \frac{23}{100} = 35.46$$

The slight variation between this calculated value & the RAM shown in a Periodic Table is due to slight differences in the mix of isotopes in different samples of the element. The official RAM in the Periodic Table is the average of many, many measurements.

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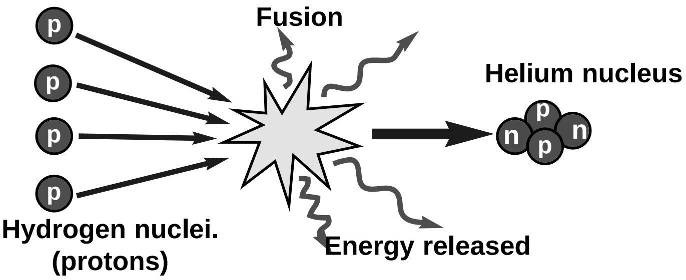
Nuclear Reactions

The nucleus of every atom is held together by the "strong nuclear force". This force is the strongest known. It is far stronger than electrical or magnetic forces, and billions of times stronger than gravity. Certain reactions in the nucleus can release this nuclear energy.

Nuclear Fusion

is when 2 small atomic nuclei are slammed together so hard that they join and become one. They join to form a larger nucleus and in the process some nuclear energy may be released.

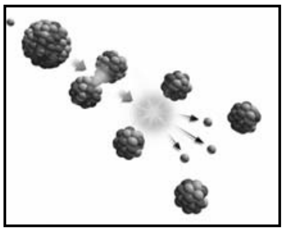


This type of reaction is called "Nuclear Fusion". It is the process which powers the stars. In a star, hydrogen is fused into helium. Helium can later be fused to form carbon atoms and so on.

In fact, we believe that the Universe was originally made entirely of very small atoms. All the larger atoms have been made by fusion in the stars.

On Earth, the fusion process only occurs in a "Thermonuclear (Hydrogen) Bomb". We would like to be able to use nuclear fusion for peaceful energy production, but so far we have not figured out how to control the process safely.

Nuclear Fission



Under certain conditions, a very large atomic nucleus (e.g. uranium or plutonium) can break apart into smaller fragments.

A nucleus which splits may release nuclear energy. It also can set off other nuclei, so the result is a "fission chain reaction".

This is the process in a nuclear reactor used to generate electricity in many countries. It is also the energy source in an "atomic bomb".

In a nuclear power station the chain reaction is controlled. The energy is used to make steam to drive an electrical generator.

In a bomb, the chain reaction runs out of control and releases the energy instantly... a nuclear explosion.

Fusion in stars was covered earlier in this module. Fission will be covered soon, but first...

Radioactivity


Henri Becquerel

In 1896, the French scientist Henri Becquerel accidentally discovered that certain minerals containing uranium were emitting a mysterious, invisible radiation. This was later called "radioactivity", meaning that the substance was actively emitting radiation.

After Becquerel's discovery, scientists soon discovered that these radiations were coming from inside the atoms of uranium... it was NOT Chemistry.


Marie Curie

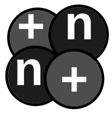
Marie & Pierre Curie were 2 of the leaders in this research & after Pierre's tragic death, Marie continued the work until her death in 1934 from a blood disorder probably caused by her exposure to radiation.

By the 1930's the research of the Curies, and others, had established:

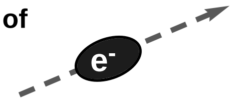
- **the nature of radioactivity.**
- **that the radiation was coming from the nucleus of atoms.**
- **the occurrence of different isotopes of each element.**
- **that some isotopes are "stable" (do NOT emit radiation), but others are "unstable" which causes them to be "radioisotopes".**

Rutherford was another research pioneer and he discovered that there were, in fact, 3 different radiations. They were quickly labelled alpha (α), beta (β) and gamma (γ) rays.

Alpha Radiation **is a stream of particles. An alpha particle is a "chunk" of nucleus, made up of 2 protons and 2 neutrons.**



Beta Radiation **is also a stream of particles: this time it is high-speed electrons ejected from the nucleus.**



Gamma Radiation **is very high frequency electromagnetic waves, similar to X-rays, but carrying even more energy.**

Gamma radiation is often (but not always) associated with the emission of alpha and beta particles.

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Alpha (α) Decay

Every atomic nucleus is held together by the "strong nuclear force". While this is very powerful, it is also very short-ranged and depends on a certain "balance" of protons & neutrons. If this balance is wrong, or the nucleus is very large, it can be unstable. It may undergo a nuclear reaction to change into a more stable form. The process can involve the emission of particles and radiation... radioactivity.

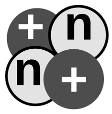
Alpha decay occurs in atoms which have a very large nucleus and are unstable. To achieve greater stability, the nucleus "spits-out" an alpha particle to get rid of excess mass and energy. As it does this, the nucleus turns into a different element. This decay may occur over and over, until the large, unstable atom "decays" into a smaller, stable atom such as lead.

Example

Uranium is well known as a radioactive substance, and "nuclear fuel" for nuclear reactors and bombs. Its most common isotope is U-238, meaning it has a mass number of 238. It decays as follows:

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

Uranium-238 | Thorium-234 | Alpha particle



The α-particle consists of 2 protons & 2 neutrons. It is the nucleus of a helium atom, so it is usually written as ${}^{4}_{2}He$

Note that the Mass No. decreases by 4, and the Atomic No. decreases by 2.

Example 2

Radium-226 undergoes alpha decay:

$$ {}^{226}_{88}Ra \longrightarrow {}^{222}_{86}Rn + {}^{4}_{2}He $$

Radium-226 | Radon-222 | Alpha particle

Hints: Use the Periodic Table to find Atomic Numbers and identify names and symbols. Note that the mass numbers AND the atomic numbers ALWAYS BALANCE (add up) on each side of a "decay equation".

Beta (β) Decay

Some atomic nuclei, of any size, have an unstable mix of protons and neutrons. If there is an excess of neutrons, a "nuclear reaction" occurs which converts a neutron into a proton, plus an electron.

Neutron → Proton + Electron

How can this happen? It seems like magic, but it shows what a strange place the quantum nucleus is. There is more detail next page; for now you must accept that it actually happens.

To understand a "decay equation" for β-decay, you need to know that electrons can be described by the following shorthand.

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

Electrons have such little mass that it counts as zero.

To make everything "balance" in a decay equation, the Atomic Number is taken to be -1.

Results of Beta-Decay

Number of neutrons decreases by 1 and protons increase by 1. (So Atomic Number goes up 1 but Mass Number does not change)
An electron is created in the nucleus, then ejected at high speed. This is the Beta particle... a high speed electron.

Examples of β - Decay

Carbon-14 is a well-known radioactive isotope which undergoes beta decay:

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

Carbon-14 | Nitrogen-14 | Beta particle

In some cases of beta-decay there may be a gamma ray emitted as well, but you cannot predict which ones do, or do not emit gamma rays.

Iodine-131 is a radioactive beta-decayer which also emits a gamma ray:

$$ {}^{131}_{53}I \longrightarrow {}^{131}_{54}Xe + {}^{0}_{-1}e^{-} + \gamma $$

Iodine-131 | Xenon-131 | Beta particle | Gamma ray

Note that once again the Mass Numbers and Atomic Numbers ALWAYS BALANCE across the equation. (Gamma emission does not affect the numbers)

Note:

There are other decay mechanisms which will not be covered here. If interested, research "positrons" & "electron-capture" to learn more.

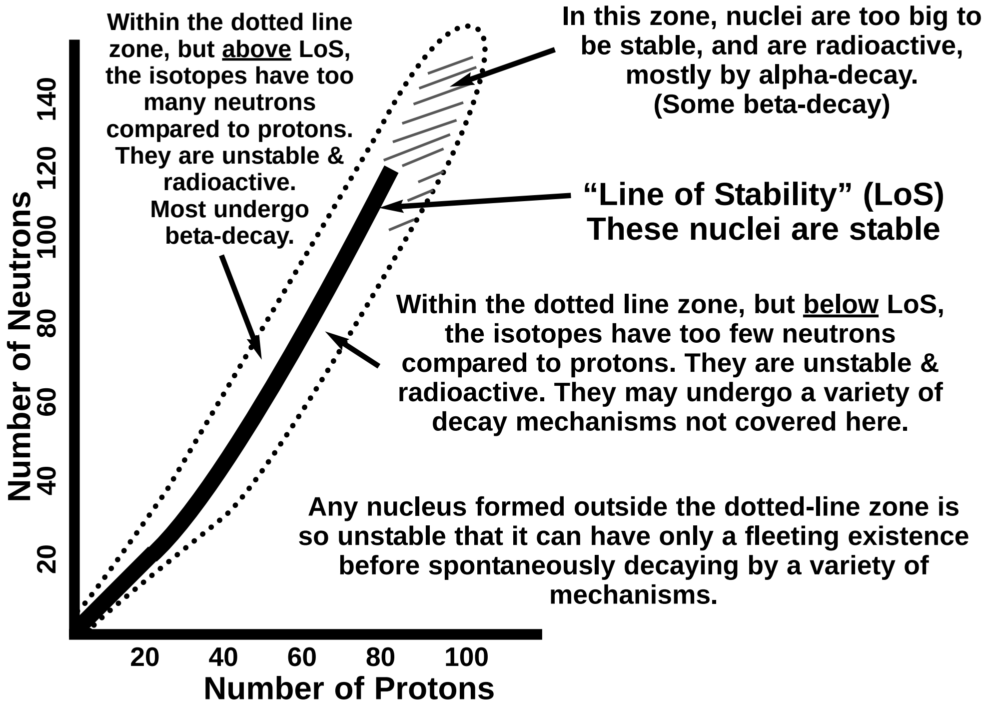
Which Decay?

**How can you tell which type of decay a particular isotope is likely to undergo?
Well, you can never be 100% sure, but there are certain patterns.**

For example, there are very few stable isotopes of really large atoms. Any isotope with atomic number more than about 80 is quite likely to be radioactive, very likely by alpha-decay.

Among smaller atoms, alpha-decay is very unlikely. However, an atom can't exist with just any combination of protons & neutrons in its nucleus. The nucleus can only be stable if the neutron/proton ratio is within certain, very narrow limits. This is best seen if all the known isotopes of all the elements are plotted on a graph, as follows:

Graph of Neutron/Proton Ratio
for all known isotopes (approximate)

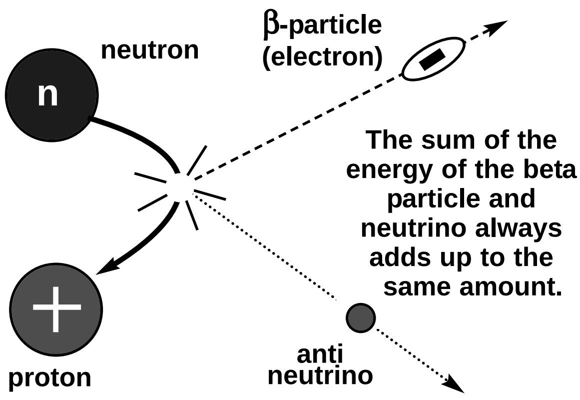


More About β-Decay... Pauli and the Neutrino

Historically, it was known that the electrons ejected during Beta decay varied considerably in their velocity, and the amount of energy they carried. This was puzzling, because it was thought that the process involved was the same in every β-decay, so why did the energy vary?

In 1931, Wolfgang Pauli suggested a quantum explanation.

What if there was another particle being produced, that no-one had detected? This "missing" particle could carry away some of the energy in varying amounts.



To have avoided detection, this hypothetical particle must have no mass (or so little that it was not measurable) and no electric charge. However, it could carry quantum energy. Pauli's idea was that there was a certain total energy involved in b-decay; some was carried off by the beta particle, the rest by the mystery particle.

Enrico Fermi did the mathematics and the whole scenario worked so well in theory that the scientific community accepted the new particle, even though it was not positively detected and identified until 1956.

This new particle was eventually christened the "neutrino" (little neutral one) and is now a totally accepted fact of the sub-atomic quantum world. In fact, there are a whole family of neutrinos; to keep it simple (KISS Principle!) the one released in beta decay is an "anti-neutrino".

The symbol used for the anti-neutrino is $\bar{\nu}$. The full equation for a beta decay is therefore: (for example)

$$^{14}_{6}C \longrightarrow {}^{14}_{7}N + {}^{0}_{-1}e^{-} + \bar{\nu}$$

Carbon-14 Nitrogen-14 β particle anti-neutrino

Note: Neutrinos were mentioned (but not explained) earlier when we described fusion in the stars. Some fusions in a star are followed by a decay involving "anti-electrons" (positrons) and neutrinos. Our examples here involve ordinary electrons and "anti-neutrinos". We now know that stars produce uncountable zillions of neutrinos throughout their lives.

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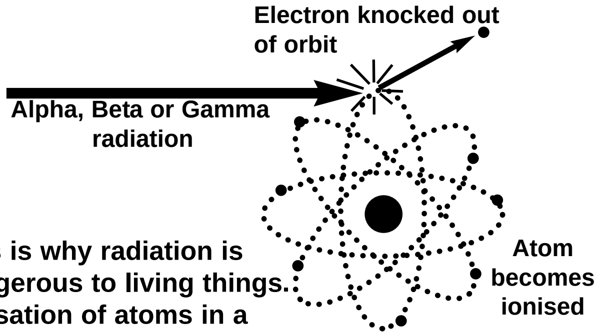
Properties of Alpha, Beta & Gamma Radiation

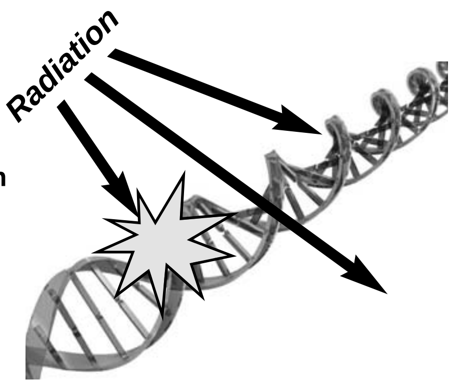
Radiation Causes Ionisation

All 3 radioactive radiations can cause ionisation... they can cause electrons to be knocked out of their orbit around an atom, turning the atom into an ion.



This is why radiation is dangerous to living things. Ionisation of atoms in a living cell can disrupt membranes, cause genetic mutations or alter the cell's DNA so that it becomes cancerous.

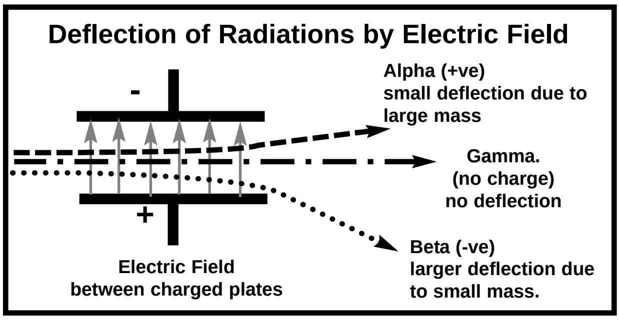
The massive ALPHA particle has the highest ionisation ability, BETA is much less ionising and GAMMA less again.



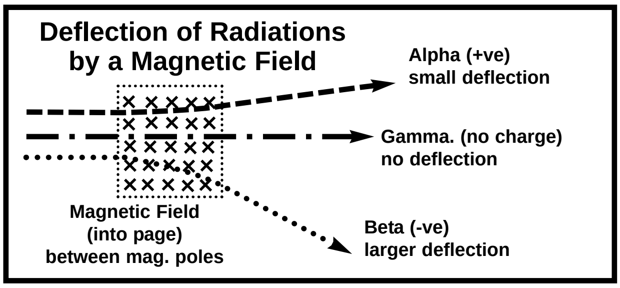
Effects of Electric & Magnetic Fields

Alpha and Beta radiations are particles and both carry electric charges. Alpha is positive (+ve), Beta negative(-ve).

This means that both Alpha and Beta can be deflected by an electric field and by a magnetic field. The deflection of alpha compared to beta will be opposite in either type of field.



Note that Gamma rays are NOT deflected by either field, because they have no electric charge.

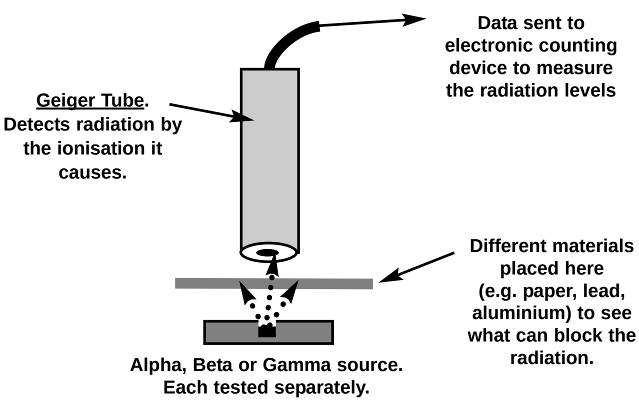


Penetrating Ability

Alpha, Beta and Gamma radiation are quite different in their abilty to penetrate through different substances.

You may have done <u>Practical Work</u> on this.

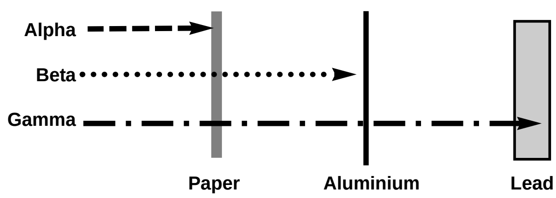
FIRST-HAND INVESTIGATION, that you may have done to test the penetration of radiation through different materials.



What You Might Have Discovered

<u>ALPHA particles have low penetrating ability</u>. They are so likely to collide and interact with atoms in their path, that they usually do not penetrate far. A few centimetres in air is as far as they'll get, and a piece of paper will stop 99% of them.

<u>BETA particles penetrate further than alpha</u>. They are less likely to interact, and so penetrate further, but rarely go more than 10-20cm in air and most can be stopped by thin metal sheets such as aluminium foil.



<u>GAMMA rays are highly penetrating</u>. They are like X-rays, only more so. Gamma can travel many metres through air and other substances. To absorb gamma rays, several centimetres of lead or a metre of concrete is merely a good start.

Complete Worksheets 10 & 11

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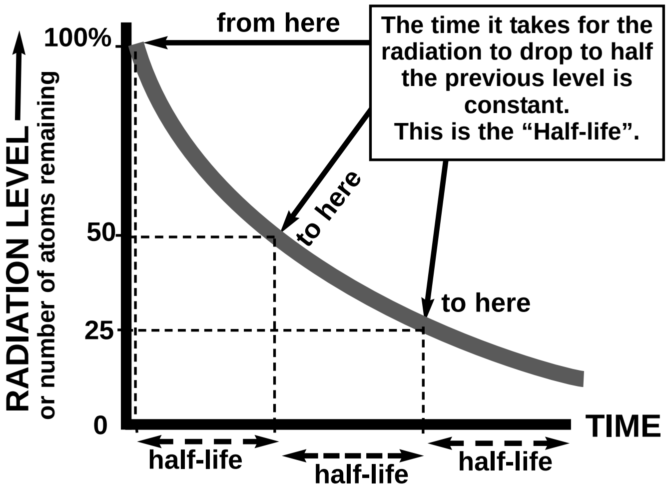
Rate of Radioactive Decay

You cannot predict when any particular unstable atom will undergo a decay event. However, in any statistically large sample of atoms of an unstable isotope, the decay events occur in a predictable, mathematical way.

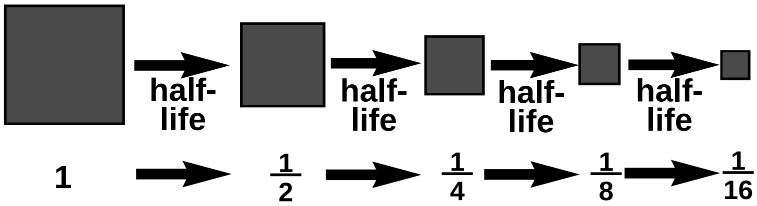
Over time, the radiation emitted (and the number of atoms remaining which have not decayed) drops exponentially as shown in the graph. The rate at which the graph declines is usually expressed by a measurement called "half-life".



Half-life of Radioisotopes

As each (equal) half-life of time goes by, half of the previous sample of atoms decays. Compared to the original starting sample, the amount remaining is a fraction as shown. For example, the diagram shows that after 4 half-lives, 1/16 of the original sample remains. (Note that theoretically this series never reaches zero.)

Original Sample



Now, please don't think that the sample shrinks in size. The atoms are still there, and the rock (or whatever) still looks exactly the same. What declines is the amount of radiation it is emitting, because the number of radioactive atoms is getting less, as each one "decays" to a new form.

Simple Example Problem

A sample containing a radioactive isotope has a radiation count of 128 units. After 12 days the radiation level has declined to 32 units.

a) What is the half-life of the isotope?
b) What radiation level would you expect after a further 18 days?

Solution

a) By halving the radiation counts:

128 → 64 → 32

you can see that 2 half-lives have gone by in 12 days. Therefore, half-life = 6 days

b) Another 18 days would be 3 more half-lives.
32 → 16 → 8 → 4
Expected radiation level = 4 units

However, you need to know the more complex mathematics of calculating the rate of decay over any given time, not just an exact number of half-lives. (at right)

Complete Worksheet 12

How Long are Some Half-Lives?

What is the typical half-life for some radioisotopes? Well, it varies enormously. Some isotopes are so unstable that their half-life is a fraction of a second. Others have a half-life of a few days.

The isotope cobalt-60 is used in medicine and industry as a source of radiation. Its half-life is 5.3 years.

Carbon-14 has a half-life of about 5,700 years. It is used to measure the age of artifacts from human history.

The isotopes most useful for measuring the age of rocks have much longer half-lives, measured in millions of years

$$N_t = N_0 . e^{-\lambda t} \quad \text{where } \lambda = \ln(2) / t_{1/2}$$

N_t = number of atoms remaining at time = t
N_0 = number of atoms present at time = 0
e = "Euler's number". $e \cong 2.7183$
The base of "natural logarithms".
λ = the "decay constant"
t = time elapsed. (units depend on those of $t_{1/2}$)
$t_{1/2}$ = half-life of the radioisotope.

Example Calculation

The half life of radioactive cobalt-60 is 5.3 years.
a) What is its "decay constant"? (hint: $\ln(2) = 0.693$)

b) What % of Co-60 atoms would remain in a sample after 12 years? (hint: If working with %, let $N_0 = 100$)

Solution

a) $\lambda = \ln(2) / t_{1/2} = \ln(2) / 5.3 = 0.693 / 5.3 = 0.131$
(Note: units of λ are the reciprocal of time units. In this case yr^{-1})

b) $N_t = N_0 . e^{-\lambda t} = 100 \times e^{-0.131 \times 12}$
$= 100 \times 0.208 = 20.8$ %
(This makes sense, since after 2 half-lives, (10.6 yr) there would be 1/4 (25%) remaining.)

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Measuring Mass & Energy in the Nucleus

Before going any further, you need to know about the commonly used methods of measuring mass and energy at the atomic level.

Atomic Mass Units

The "atomic mass unit" (u) is a measure of mass devised for convenience at the atomic level. Roughly speaking, both a proton and a neutron have a mass of 1 u, although in the calculations following, you need to be much more precise. Obviously, 1 u is a very small mass:

$$1\ u = 1.661\times10^{-27}\ kg$$

You need to be able carry out calculations using either unit, so the following data may be useful.

	Proton	Neutron
Mass (in kg)	1.673×10^{-27}	1.675×10^{-27}
Mass (in u)	1.0073	1.0087

Mass Defect in the Nucleus

It was realised that incredibly powerful forces were operating within the atomic nucleus. How could such forces arise?

The answer lies in the fact that the mass of every atomic nucleus (except hydrogen) DOES NOT ADD UP.

If you add up the mass of all the protons+neutrons in any nucleus,

the total is always more than the actual measured mass of the whole nucleus.

Mass of Protons + Neutrons > Mass of Whole Nucleus

This difference is called the "Mass Defect". It's as if a little bit of mass "went missing" when the protons and neutrons joined together to form the nucleus.

Where is the missing mass?

It has converted to energy...

$$\boxed{E = mc^2}$$

(you should have known that Einstein would be involved sooner or later!)

...to provide the "Binding Energy" of the Strong Nuclear Force which holds the nucleus together.

Einstein had developed his most famous equation as part of his Theory of Relativity. He never anticipated that it would find another use...

Energy in Electron-Volts

The "electron-volt" (eV) is an energy unit that is convenient because the energy of sub-atomic particles has traditionally been measured by their behaviour within electric fields.

1 eV is the energy gained by an electron accelerating in an electric field with a potential difference of 1V. 1 eV is an extremely small amount of energy:

$$1\ eV = 1.602\times10^{-19}\ \text{joules of energy}$$

so the unit often used is the mega-electron-volt (MeV)

$$1\ MeV = 1\times10^{6}\ \text{(one million) eV}$$

This is convenient when dealing with individual atoms or particles.

Example Calculation

The nucleus of a carbon-12 atom contains 6 protons and 6 neutrons. The nucleus is known to have a mass = 11.9967 u = 1.993×10^{-26} kg

Calculate the Mass Defect, and total Binding Energy.

Solution

In kg and joules

Mass of 6 protons
$= 6 \times 1.673\times10^{-27}$
$= 1.004\times10^{-26}$ kg

Mass of 6 neutrons
$= 6 \times 1.675\times10^{-27}$
$= 1.005\times10^{-26}$ kg

Total particle mass
$= 2.009\times10^{-26}$ kg

∴ Mass defect
$= 2.009\times10^{-26} - 1.993\times10^{-26}$
$= 1.600\times10^{-28}$ kg

In u and MeV

Mass of 6 protons
$= 6 \times 1.0073$
$= 6.0438$ u

Mass of 6 neutrons
$= 6 \times 1.0087$
$= 6.0522$ u

Total particle mass
$= 12.0960$ u

∴ Mass defect
$= 12.0960 - 11.9967$
$= 0.0993$ u

These are the same, just different units

In kg and joules

This missing mass has converted to binding energy according to

$E = mc^2$
$= 1.6\times10^{-28} \times (3.00\times10^{8})^2$
$= 1.44\times10^{-11}$ J

In u and MeV

Each 1 u converts to 931.5 MeV of energy (This value is in your Physics Data Table)

So, binding energy
$= 0.0993 \times 931.5$
$= 92.50$ MeV

These are the same, just different units

From here on, all calculations will be done in atomic mass units (u) and MeV.

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Nuclear Fission

In the 1930's, it was discovered that bombarding "target" atoms with alpha particles could occasionally produce a transmutation to a new radioactive isotope. For example...

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

Aluminium, α-particle, new isotope of phosphorus, neutron

In Italy, brilliant young physicist Enrico Fermi (1901-54) decided that using neutrons as "atomic bullets" would be even more productive.

In 1934 he began bombarding every possible element, in turn, with neutrons and studying the resulting radioactivity to detect any new radioisotopes. Over 40 were discovered very quickly. For example:

$$ {}^{19}_{9}\mathrm{F} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{20}_{9}\mathrm{F} $$

Fluorine, Neutron, New, previously unknown radioisotope of Fluorine

In one experiment he bombarded uranium atoms with neutrons, confidently expecting to produce atoms of "transuranic" elements. The radiation "signatures" detected were unexpected and puzzling, but he was focused on other things and failed to investigate further.

Fermi had "split" the nucleus, but it was another 4 years before other scientists in Germany confirmed what had happened. In his sample of uranium were atoms of U-235 which had absorbed a neutron, then totally disintegrated:

$$ {}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{92}_{36}\mathrm{Kr} + {}^{141}_{56}\mathrm{Ba} + 3\,{}^{1}_{0}\mathrm{n} $$

Uranium, Neutron, Krypton isotope, Barium isotope, 3 extra neutrons released.

These can set off other atoms in a "chain reaction"

This is Nuclear Fission; the splitting of the nucleus., with enormous energy release, due to a mass defect and $E = mc^2$.

Meanwhile, Fermi had continued on with his work, and was awarded the Nobel Prize of 1938 for his production of new radioactive materials.

With war looming in Europe and a Fascist regime in Italy, Fermi and his Jewish wife used attendance at the Nobel Prize ceremony in Sweden to flee to the USA, where Fermi was immediately accepted into the scientific community.

By then he was aware of nuclear fission and its huge energy potential, and that the experiments confirming fission had been done in Nazi Germany. On the eve of World War II, it seemed that the knowledge to develop an "atom bomb" was in the hands of a dangerous enemy.

The Manhattan Project

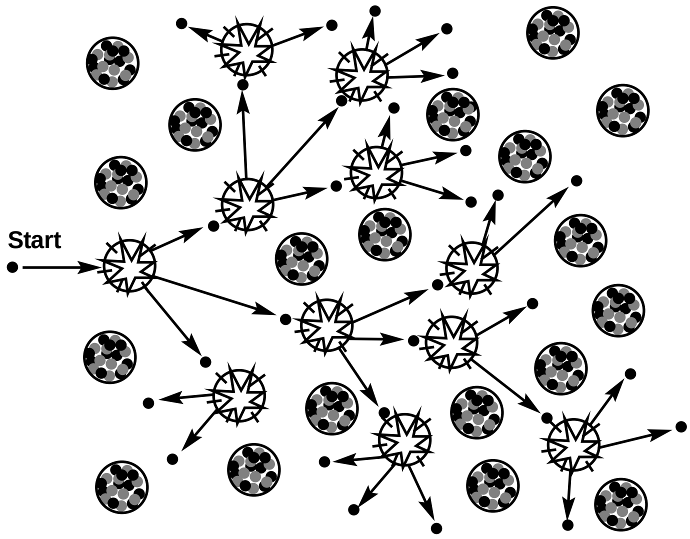
Following a "letter of concern" (outlining the danger of nuclear research in Nazi Germany) from Einstein to the President of the USA , the top secret "Manhattan Project" was set up in 1942. Its objective was to research nuclear fission and develop an "atomic bomb" if possible.

The first step was to discover if a self-sustaining fission chain-reaction was possible. Enrico Fermi was appointed the leader of the scientific team. He designed the reactor or "nuclear pile", which was built in a squash court at the University of Chicago.

In December 1942 the reactor achieved the first self-sustaining, controlled chain reaction.

The Fission Chain Reaction

Since fission is set off by a neutron, and since it releases more neutrons, it follows that a chain reaction can occur, in which each atom which splits can set off more.



If the amount of "fissile" atoms is below a certain "critical mass", most neutrons escape without striking another nucleus, so the chain reaction is not self-sustaining and dies away.

In a critical mass of "fissile" atoms, if every fission sets off (say) 2 more, then the chain reaction grows exponentially within a fraction of a second. This is uncontrolled fission, and results in a nuclear explosion of devastating power... an "atomic bomb".

If a neutron-absorbing material (such as cadmium) is present, it is possible to absorb many of the neutrons so that each fission sets off exactly one other. This is controlled fission and is what Fermi achieved in his "pile" in 1942, and what occurs in every nuclear power station.

There are only 2 nuclei which will readily undergo fission:

$$ {}^{235}_{92}\mathrm{U} \qquad {}^{239}_{94}\mathrm{Pu} $$

Uranium-235 which occurs naturally in uranium ores, but in very small amounts.

Plutonium-239 which can be made from U-238 by neutron bombardment in a nuclear reactor.

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Mass Defect During Nuclear Fission

The enormous energy released by nuclear fission is due to a "mass defect" between the starting nucleus and the product nuclei.

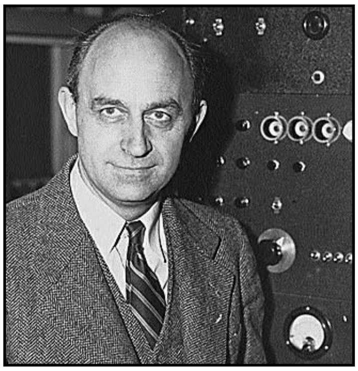
For example, in the fission of Uranium-235:
(Note: fission products can vary)

$$ {}^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{148}_{57}La + {}^{85}_{35}Br + 3\,{}^{1}_{0}n $$

U-235 mass	neutron mass	La-148 mass	Br-85 mass	3 neutrons mass
235.0439 u	1.0087 u	147.8114 u	84.8917 u	3.0261 u

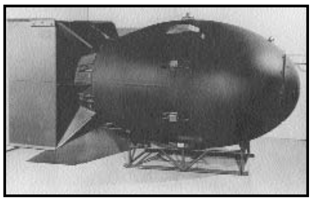
Total Mass before Fission 236.0526 u

Total Mass after Fission 235.7292

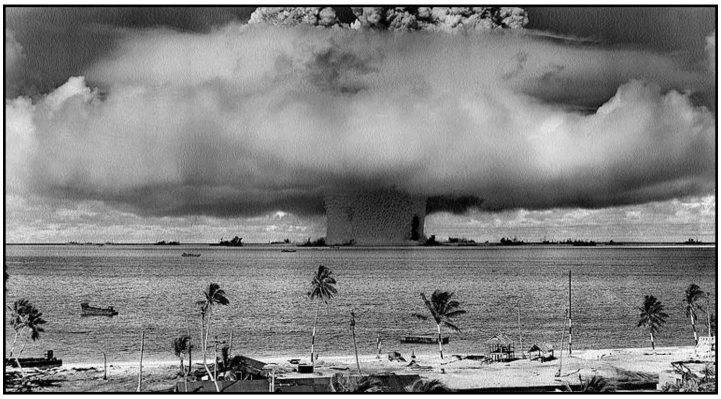


Enrico Fermi in 1943 working on the "Manhattan Project"

Below: This is the plutonium fission bomb, nicknamed "Fat Boy", which destroyed the city of Nagasaki in 1945.



Below: Atom bomb test by USA in 1946 at Bikini Atoll, Pacific Ocean.
Later that year, a French fashion designer released a new, daring, 2-piece style of swimwear. It was named "bikini" to take advantage of the great public interest in nuclear weapons. Yes, that's where the name came from!



Mass Defect = (Mass Reactants - Mass Products)
= 236.0526 - 235.7292 = 0.3234 u

Energy yield per fission:
Remember that 1 u of mass → 931.5 MeV of energy

So, energy released = 0.3234 x 931.5
= 301.2 MeV
(This equates to about 5×10^{-11} joules of energy)

The energy released might seem a very small amount, but this is from just one atom. In (say) 10kg of uranium there are about 2.5×10^{25} atoms. If all of these were to undergo fission, the total energy released would be about 1×10^{15} joules, all released in a split second, in the case of an atom bomb. This is the energy generated by an average size power station in about 30 years.

Of course, the Conservation of Mass & Energy applies. The total energy before the reaction (including the $E=mc^2$ energy equivalent of the masses involved) is exactly the same as total energy after the reaction.

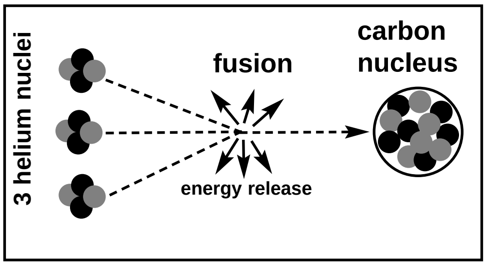
Mass Defect in Fusion

As an example, consider the "helium-burning" fusion which occurs in a "Red-Giant" star, covered earlier.

$$ 3\,{}^{4}_{2}He \longrightarrow {}^{12}_{6}C + \text{energy} $$

Total Mass before Fusion 3 x 4.0026 u = 12.0078 u

Total Mass after Fusion 11.9967 u



As was covered earlier, fusion in stars can produce larger & larger nuclei to eventually fill the Periodic Table.
For nuclei up to about the size of iron, the fusions release more heat & radiation to keep the star "burning". Beyond iron, the fusions need to absorb some energy to make the larger nuclei.

Mass Defect = (Mass Reactants - Mass Products)
= 12.0078 - 11.9967 = 0.0111 u

Energy yield per fusion: 1 u mass → 931.5 MeV energy

So, energy released = 0.0.0111 x 931.5
= 10.34 MeV

Once again, the Conservation of Mass & Energy applies, with conversion of mass into "binding energy" (according to $E = mc^2$) occurring.

Mass Defect in Radioactivity

Complete Worksheet 13

We will NOT attempt to calculate a "mass defect" for an example of a radioactive decay. You can try it for yourself, but you will probably get a negative mass defect (= a gain in total mass) which doesn't make sense for a spontaneous reaction. The problem is that the masses we use are "rest masses".

In radioactivity reactions, α or β particles may come out of the nucleus at relativistic velocities. This complicates the calculation. There is also the energy carried away by gamma radiation and/or neutrinos. Just be assured that Conservation of Mass & Energy is alive & well and rules supreme as always!

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5. Deep Inside the Atom

The "Standard Model" of Matter

After 120 years of scientific research into the sub-atomic quantum universe, just what is the latest "picture" we have for the structure of matter? Our modern understanding is known as the "Standard Model", and is a description of both matter and energy (since these are inter-changeable) at its most fundamental level.

The 4 Fundamental Forces

The Standard Model describes the ways that matter and energy interact with each other via four fundamental forces. These forces have, in the past, been described as "force-fields" such as the electric, magnetic & gravitational fields.

1. Gravity

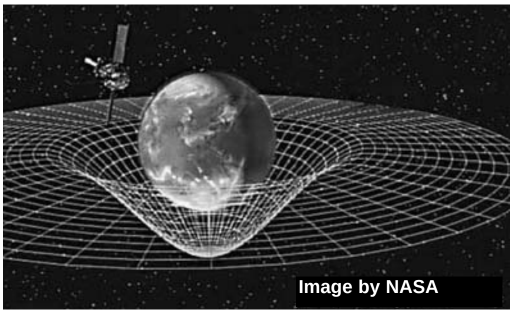


Image by NASA

If you drop a brick on your toe, you may assess gravity as being a pretty powerful (& painful) force. In fact, it is by far the weakest of all and at the atomic scale is billions of times weaker than all the others.

At astronomical scales, gravity is best understood as the curvature of space-time as described in General Relativity. It is responsible for the formation of galaxies, stars & planets, as well as falling bricks.

At atomic scales, there are theoretical reasons to suspect that gravity is due to quantum particles called "gravitons", but these have not yet been proven to exist.

At the everyday macroscopic scales where humans exist, gravity is best understood as a "force-field", so do not drop that brick!

2. Electromagnetism

Originally it was thought that electricity & magnetism were 2 separate forces, but since the time of Maxwell's Theory in the 19th century, they have been "unified" as "electromagnetism".

We do not notice how powerful this force is, because all atoms contain electric & magnetic particles whose opposite charges & poles tend to cancel out at macroscopic levels. We only notice the effects of this force when temporary imbalances occur, such as in a lightning discharge.

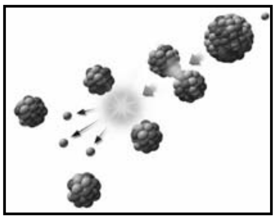
Electromagnetism controls chemical reactions, because electrons interact to form, or break, chemical bonds. Electromagnetism is of course, responsible for all EM radiations, including light and for all our electrical & electronic technology.

3. Weak Nuclear Force

This fundamental force acts inside the atomic nucleus and is responsible for the events occurring during radioactive decay.

It is much weaker than electromagnetism and has effects only within the atomic nucleus.

4. Strong Nuclear Force



This force is the most powerful of all and operates only within the atomic nucleus. It is equal to the "binding energy" which holds nuclei together and for the release of energy during nuclear fission or fusion.

More about this when we discuss the Standard Model with regard to fundamental particles.

Unification of the Forces

Just as the electrical & magnetic forces were "unified" into electromagnetism, in the 1970's it was proven that electromagnetism and the weak nuclear force are manifestations of a single, fundamental force now called "Electroweak".

The idea is that, at the time of the Big-Bang, these forces were all one fundamental force. As the "energy-density" of the expanding Big-Bang declined, these forces separated into seemingly different force phenomena.

If matter is subjected to high enough energies in "particle accelerator" experiments (more soon) these forces become the same thing... they are unified. This has been verified by experiments and can also be explained in mathematical detail by modern Quantum Mechanics theory.

The GUT & the ToE

An important point to note is that electroweak and strong nuclear forces are both quantum fields involving particles (like the light photon) which are all "particle-waves" and have a variety of quantised properties.

Progress is currently being made to unify the strong nuclear force with electroweak to form a "Grand Unified Theory" ("GUT"). It is thought that very early in the Big-Bang, all these forces were one. Modern high-energy experiments aim to prove this, if the energy of the early Big-Bang can be achieved in the particle-accelerators.

What about gravity? Can it be unified with the others? Many scientist think so, and some research aims to find the "Theory of Everything" ("ToE"). So far, gravity cannot be reconciled with Quantum Mechanics. Finding the hypothetical "graviton" particle would be a major breakthrough.

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Finding the Fundamental Particles

For much of the 19th century, atoms were thought to be fundamental particles of matter. They were imagined as indivisible, unbreakable particles and NOT made from any smaller parts. In 1897, Thomson's experiment (discovery of electrons) changed that opinion for ever and over the next 30+ years came many discoveries; radioactivity, protons & neutrons, particle-wave properties, Quantum Mechanics, etc.

During this time, some scientists turned their radiation-detectors upwards or flew them in balloons and soon discovered strange radiations coming from space. Initially thought to be high energy gamma waves, this radiation was called "cosmic rays". Later, it was figured out that it is high-velocity protons & alpha particles coming from the Sun, or other stars, and creating showers of "cosmic rays" as they struck atoms in the upper atmosphere.

The "cosmic rays" turned out to be cascades of strange new particles given names like "muons", "mesons" & pions. There were also anti-particles such as "positrons" (positively-charged electrons). These new particles were similar in some ways, but also different from, electrons & protons. This raised new questions about the true nature of matter and whether protons & neutrons were really "fundamental" particles.

The "Atom-Smashers"

Taking a lesson from the cosmic rays, scientists began accelerating ions, protons or electrons with powerful magnetic fields in the laboratory. Accelerated (in vacuum) to relativistic velocity, these "atomic bullets" were collided with each other or smashed into targets in the experiments. Sensitive detectors were developed to study the particles & energy spraying outwards from each collision. (and extending what Rutherford, Chadwick, Fermi and others had done before.)

Part of the LHC at CERN
image by Maximilien Brice. CCA-SA 4.0 Int

This tube forms a ring 27 km in circumference. It contains a near-perfect vacuum. Within it, protons at close to the speed of light smash each other with energies approaching those in the early Big-Bang.

CERN and the LHC

Currently the largest & most powerful scientific facility to do this is located underground on the border between France & Switzerland.

The facility is run by an organisation called <u>CERN</u>, which is a French acronym for "European Nuclear Research Organisation". It was formed in the 1950's and is dedicated to high-energy Particle Physics. It has 23 member countries who run it & fund it co-operatively.

The facility cost many billions of dollars to build & millions per year to maintain. It has a technical staff of over 2,000, hosts about 10,000 visiting experimenters per year and feeds its data world-wide for analysis by thousands more scientists. The internet was first invented as part of the computer network to distribute CERN data.

The biggest particle-accelerator at CERN (there are several) is the "<u>Large Hadron Collider</u>" ("LHC"). It was first used in 2008 and by 2012 had confirmed the existence of the theoretical particle, (Higgs boson) which we believe is responsible for giving <u>mass</u> to all matter.

At the time, the mass media called it the "<u>God-particle</u>", because it has "created" the Universe as we know it. By endowing other particles with their mass, the Higgs boson gives atoms the property which allows gravity to form them into stars & planets.

The "Particle Zoo" & Quarks

Through the 1950-60's the particle-collision experiments carried out at a variety of laboratories in Europe & USA kept discovering more & more exotic sub-atomic particles. This large population was jokingly called the "Particle Zoo". This huge variety defied explanation!

In 1964, two American physicists independently put forward a theoretical model to explain & simplify the "zoo". Based firmly in Quantum Mechanics, the model proposed the existence of a family of particles called "quarks". Quarks have mass and carry fractional electric charges, (compared to the electron) plus other quantum properties which have been called "<u>colour</u>" & "<u>flavour</u>". (but have nothing to do with the normal meaning of those words)
It was proposed that <u>protons</u> & <u>neutrons</u> (and many other members of the "zoo") are NOT fundamental particles, but composed of certain combinations of quarks.

This theoretical idea was soon tested by experiments at the <u>Stanford Linear Accelerator Centre</u> ("SLAC") in California, USA. In 1968, while bombarding protons with high-velocity electrons, evidence was found for 3 quarks inside a proton. Later experiments at SLAC and CERN (and other labs) were able to isolate & indentify a family of 6 individual quarks between mid 1970's to 1995.

So, what are the true "fundamental" particles?
The Standard Model for particles is next.

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The Standard Model for Particles

FUNDAMENTAL PARTICLES

QUARKS

There are 6 different quarks, some with whimsical names such as "charm" & "strange". Quarks have mass, carry electric charge and also the quantum properties called "colour" & "flavour". This means they can "feel" and interact with ALL 4 fundamental forces.

Each quark has an electric charge of either +2/3 or -1/3 compared to the electron.

Protons & Neutrons Contain Quarks

- **Protons are each made of 3 quarks with charges = +2/3 +2/3 -1/3 = +1**
- **Neutrons also contain 3 quarks with charges = +2/3 -1/3 -1/3 = 0**

Mesons

These are nuclear particles composed of 2 quarks. Within an atomic nucleus, the mesons act as "carriers" of the strong force and hold a nucleus together. In this role, they act in a similar way to the bosons (right).

Outside the nucleus, mesons are unstable and rapidly decay into various leptons & gamma radiation, as their "weak nuclear force" interactions take over.

When an atomic nucleus is "smashed" apart, a vast array of different mesons may appear, each then decaying into even more particles.
This is why the "cosmic rays" and the "particle zoo" was so confusing to earlier researchers.

LEPTONS

are fundamental particles with very small masses. They include the electron, and the neutrino family. (There are several types of neutrino)

Some leptons (such as the electron) carry electric charge and the "flavour" quantum property. They have mass, charge & "flavour", so this means they interact with gravity, electromagnetic & weak nuclear forces, but NOT the strong nuclear force. The strong force relies on the "colour charge" quantum property.

As well as being the particles which flow in an electric current, electrons are at home in orbit around a nucleus. Remember too, that they have wave properties and form (de Broglie's) "standing waves" within (Bohr's) allowed orbits.

When formed in the nucleus during beta decay, the electron, and an anti-neutrino, are instantly ejected at high speed.

BOSONS

The massless "Gauge Bosons" are the means by which all the other particles exert one or more of the fundamental forces on each other.

Photons

The best known is the "photon" of electromagnetic radiation, such as light. Photons will interact with any lepton or quark (or quark-composite) which carries electric charge.

Gravitons

Gravity is thought to involve "gravitons", but these have not yet been proven to exist.

Gluons

The quarks inside a proton, neutron or meson are held together by "gluons" which interact only with particles which have "colour charge".

W & Z Particles

These carry weak nuclear force, responsible for the re-arrangements of quarks which occur during radioactive decay. They interact with any particles carrying the "flavour charge".

Higgs Boson

is quite different to all the "gauge bosons" above. Higgs is a "scalar boson" and has a very large mass. It interacts with quarks & leptons to imbue them with the property we call "mass".

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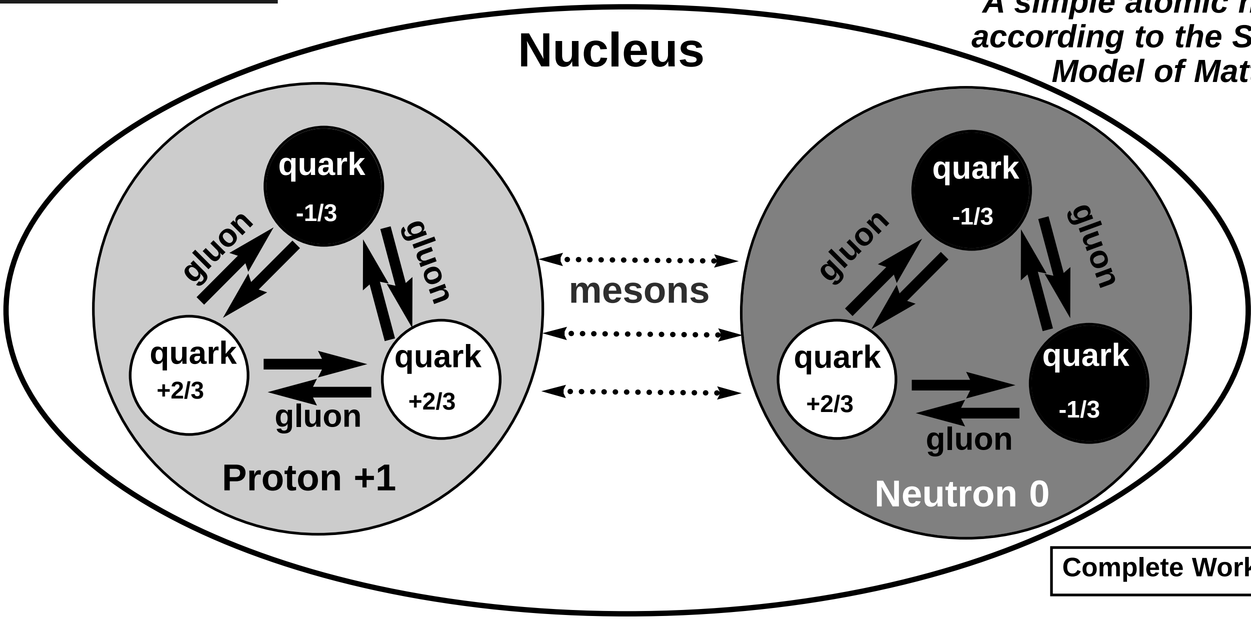
The Standard Model *(cont.)*

A simple atomic nucleus according to the Standard Model of Matter



Complete Worksheet 14

This diagram may raise a question about the Strong Nuclear Force... which particles actually mediate the force? Is it the gluons (binding the quarks together) or is it the mesons holding the nucleons together?

Actually, it is both!

The gluon interaction between quarks is especially powerful, but the mesons (each composed of 2 "opposite-charge" quarks) carry a smaller "residual" part of the force. This "residual" force has a very short range, which limits the size of atomic nuclei. Once a nucleus is bigger than about 200 nucleons, the force cannot hold them together indefinitely and radio-active decay may result.

Anti-Particles and Anti-Matter

We also know that for every quark (and quark-based particle) and lepton that exists, there is also a corresponding anti-particle. For example, there are electrons, and there are anti-electrons ("positrons") which have the same mass, but opposite electric charge. There are also anti-protons, anti-neutrons, and so on. As you know, the other particle formed in beta-decay is an anti-neutrino. Theoretically, "anti-matter" could exist, with atoms made entirely of anti-particles.

When any particle and its anti-particle meet, they mutually annihilate each other... all the mass is converted into energy (photons of gamma radiation) according to $E = mc^2$.

One of the remaining mysteries is why (some time in the early Big-Bang) the Universe came to be made of mostly "normal" matter. Theory suggests there should have been an equal amount of anti-matter.