Antonine Physics AS

Topic 2 Particle Physics

How to Use this Book

How to use these pages:

- This book intended to complement the work you do with a teacher, not to replace the teacher.
- Read the book along with your notes.
- If you get stuck, ask your teacher for help.
- The best way to succeed in Physics is to practise the questions.

There are many other resources available to help you to progress:

- Web-based resources, many of which are free.
- Your friends on your course.
- Your teacher.
- Books in the library.

This is an electronic book which you can download. You can carry it in a portable drive and access it from your school's computers (if allowed) as well as your own at home.

Particle Physics is very much at the cutting edge of Physics as I write this.

There are many different sub atomic particles, such as quarks and mesons. The nucleus of an atom is not a collection of black and red billiards balls as you learned at GCSE, but a very dynamic entity with particles being swapped around all the time.

Investigation into sub atomic physics is a massive undertaking, not just with highly expensive and power-hungry equipment, but also with some of the finest physics brains in the world. You will meet the so-called "particle zoo", which includes a menagerie of mesons, leptons and baryons. Even these names sound weird.

Particle Physics continues to capture the imagination.

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2.011 Constituents of the Atom

The simplest model of the **atom** is shown in the diagram below:

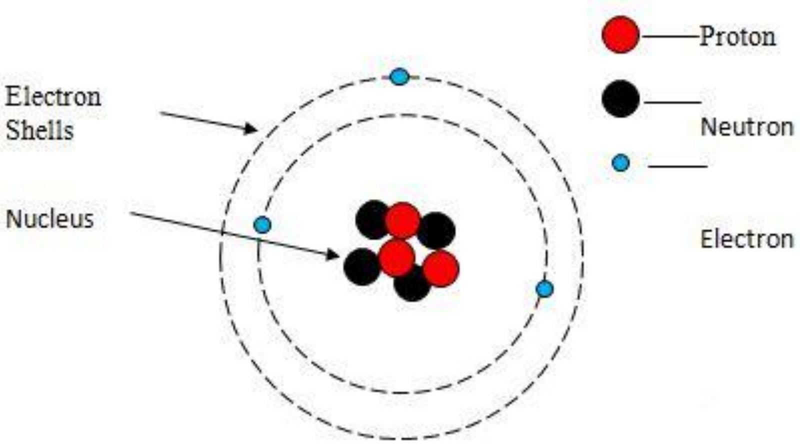

Figure 1 Structure of a simple atom

This is the layout of a **lithium** atom, with three protons, three electrons, and four neutrons. The protons and neutrons are, of course, found in the nucleus. They are called **nucleons**. The electrons are found in shells **orbiting** the nucleus.

It is important to understand:

- The nucleus is very small compared to the atom, about 10 000 times smaller. The diameter of an atom is in the order of 10^{-10} m, whereas the diameter of the nucleus in the order of about 10^{-15} m.
- The atom is a very dynamic entity. The diagram shows a stylised representation; the reality is that nucleons are moving about and changing shape all the time.

The properties are shown in the table below.

Property	Electron	Proton	Neutron
Charge	-1 e	+1 e	0
Mass	9.11×10^{-31} kg	1.67×10^{-27} kg	1.67×10^{-27} kg
Relative Mass	1/1836	1.0000	1.0004

Notice that:

- The electron and the proton have the same value of charge, but the signs are different. We also use a quantity for the charge called **electronic charge unit**, e.
- $1e = 1.602 \times 10^{-19}$ C.
- The neutron has a very slightly higher mass than the proton.

2.012 Charged Atoms

Atoms are **neutral** because the positive charge and the negative charge **cancel out**. If an electron is removed, the atom becomes positively charged and we call the charged atom an **ion**. If an electron is added, we get a negative ion. The protons never move.

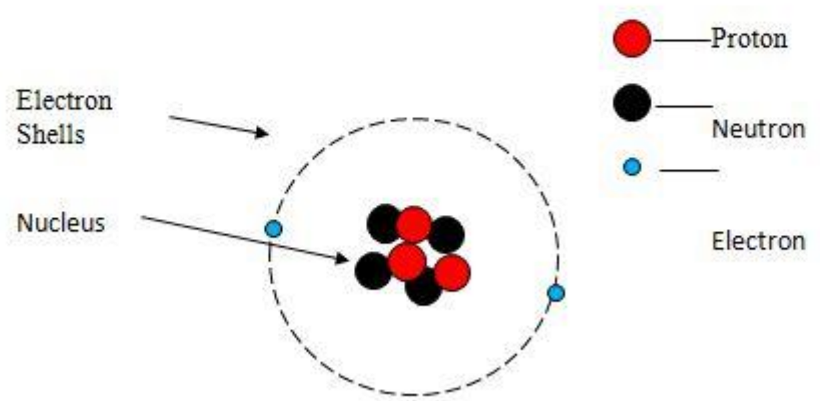

Figure 2 Structure of a simple ion

The movement of electrons between atoms is at the heart of **chemical reactions**.

2.013 Isotopes

Different atoms are distinguished by their numbers of protons and neutrons. We write the symbols using the following notation:

$$^{A}_{Z}\mathrm{X}$$

Figure 3 Isotope Notation

- A is called the **nucleon** number, or the **mass** number. It is the total number of nucleons.
- Z is the **proton** number or the **atomic** number, which is the number of protons. The number of protons determines the element.

Be careful not to confuse atomic number with the symbol A. We will refer to A as the **nucleon number** in these notes and Z as the **proton number**.

We can determine the **number of neutrons** simply by subtracting the **proton number** from the **nucleon number**.

No of neutrons = $A - Z$

Atomic particles are always in whole numbers.

- **Isotopes** have the same numbers of protons, but different numbers of neutrons.
- Isotopes have **the same** physical and chemical properties.
- If the proton number is altered, the element changes.
- Some isotopes are radioactive, as the nuclei are unstable.

Chemical reactions involve the **electrons** of the **outer shells**. **Nuclei** are not involved in any way and remain **totally unaltered** even in the fiercest chemical reactions.

Carbon-14 looks like this (*Figure 4*).

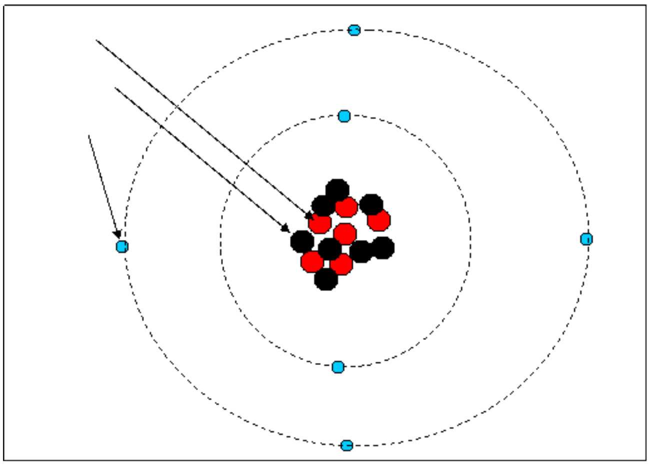

Figure 4 Carbon-14 is an isotope of Carbon

Carbon 14 is an **unstable isotope**. It **decays** so that one of the neutrons turns into a proton.

2.014 Charge to mass ratio

This is an important quantity to particle physicists. If two particles have the same **charge to mass ratio**, they will be deflected by the same amount by magnetic fields or electric fields (you will study these at A2). Charge to mass ratio is also called **specific charge**.

The charge to mass ratio is given by this equation:

Charge to mass ratio = charge (C) ÷ mass (kg)

$$\text{Charge to mass} = \frac{q}{m}$$

The units are **coulombs per kilogram** (C kg^{-1})

The electron has the highest charge to mass ratio, as it's the smallest particle. For an electron, the calculation is quite simple:

Charge to mass ratio = 1.6×10^{-19} C ÷ 9.11×10^{-31} kg = 1.76×10^{11} C kg^{-1}

For a nucleus (without the electrons) we have to be a bit more careful, as shown in the worked example:

Worked Example What is the charge to mass ratio of a helium nucleus (alpha particle)?
Answer We will assume that the proton and the neutrons have the same mass, 1.67×10^{-27} kg. In a helium nucleus, there are **2 protons** and **2 neutrons**, making up **4 nucleons**. $\text{Charge to mass ratio} = \dfrac{2 \times 1.6 \times 10^{-19}\ \text{C}}{4 \times 1.67 \times 10^{-27}\ \text{kg}}$ $= \mathbf{4.85 \times 10^{7}\ C\ kg^{-1}}$

For a **neutral atom**, the charge to mass ratio is **zero**, because there is no charge.

For the **Lithium ion**, Li^+, there is a charge of 1.6×10^{-19} C. There are 7 nucleons (3 protons, and 4 neutrons).

$$\text{Charge to mass ratio} = \frac{1 \times 1.6 \times 10^{-19}\ \text{C}}{7 \times 1.67 \times 10^{-27}\ \text{kg}} = \mathbf{1.37 \times 10^{7}\ C\ kg^{-1}}$$

In the exam, read the question carefully. Make sure that you are doing a **charge to mass ratio**, not the **charge on the ion**. **Specific charge** is the same thing as the charge to mass ratio. The unit for charge to mass is C kg^{-1} not N kg^{-1}.

2.015 Rutherford Scattering (Extension)

In the early part of the last century, the accepted model of the atom was proposed by J J Thompson in his **plum pudding** model. This consisted of a matrix of protons in which were embedded electrons. Although this may sound ridiculous today, scientists previously believed that the atom could not be broken down at all.

Ernest Rutherford (1871 – 1937) used **alpha particles** to study the nature of atomic structure with the following apparatus:

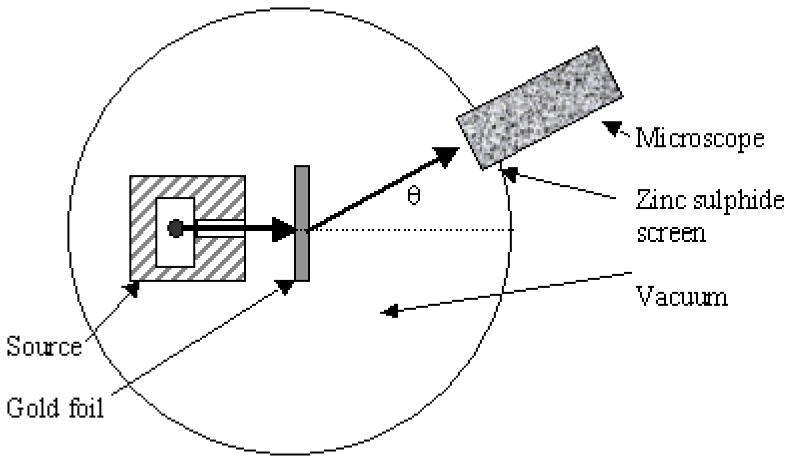

Figure 5 Rutherford's Alpha Scattering Apparatus

Rutherford was using alpha particles (**helium nuclei**) as nuclear bullets to smash up the atoms; he wanted to see atoms bursting like watermelons. But...

His observations are best illustrated with this diagram

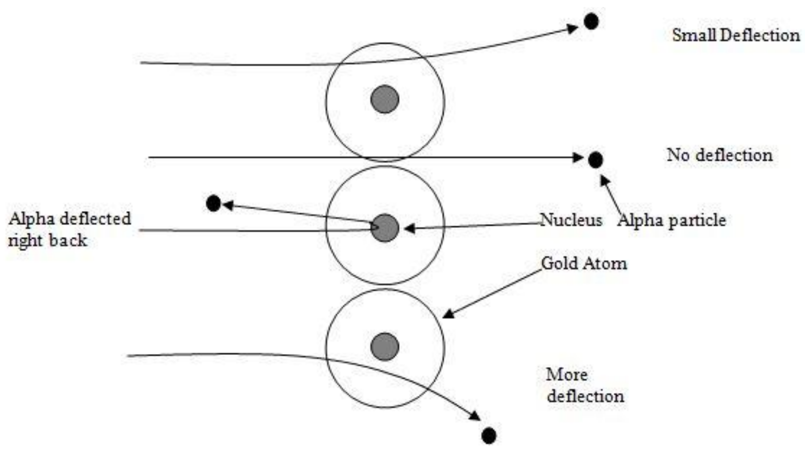

Figure 6 Alpha particles deflect ed by gold nuclei

Instead of bits of atom, Rutherford found that a small proportion of the alpha particles were deflected (*Figure* 6), while an even smaller proportion bounced right back. From analysis of these observations, he concluded:

- Most of the atom was empty space.
- The positive charge was concentrated in a very small space
- The radius of the nucleus was in the order of 3×10^{-14} m.

- The alpha particles that were deflected back had to be travelling in a line with the nucleus.

Rutherford's estimates were not far out. Later research has shown the nuclear radius to be in the order of 1.5×10^{-14} m. However, the boundary is not sharp, but rather fuzzy, as the nucleus is very dynamic.

Tutorial Questions for 2.01

2.01.1

Refer to *Figure 1*. How many protons neutrons and electrons are there in the lithium atom?

2.01.2

A carbon atom has 6 protons and 6 neutrons. Draw out the carbon atom in a similar way to the lithium atom in *Figure 1*.

2.01.3

What is the total charge of a carbon nucleus?

(a) in electronic charge units
(b) in coulombs

2.01.4

What is the total charge of the electrons?

(a) in electronic charge units
(b) in coulombs

2.01.5

Carbon 14 is an isotope of Carbon. Complete the table:	
Protons	
Neutrons	
Electrons	
Write out carbon-14 in isotope form	

2.01.6

Draw out the new atom in question 2.01.5. How many protons, neutrons and electrons does it have? What is it?

2.01.7

A sulphur atom has a nucleon number of 32. What is the specific charge of an S^{2-} ion?

Mass of a nucleon = 1.67×10^{-27} kg; $e = 1.6 \times 10^{-19}$ C.

2.01.8

What led Rutherford to conclude that the nucleus was very tiny and had a positive charge?

Tutorial 2.02 Stable and Unstable Nuclei

All Syllabi

Contents

2.021 What holds the Nucleus together?

The nucleus is a very small space, so the repulsion force is very strong. Protons repel each other, because they are like charges - the **electrostatic** force. This means that the nucleus should fly apart, but we know it doesn't. There has to be a force that counteracts the repulsion:

- It is called the **strong force**.
- Neutrons and protons provide the **strong force**.

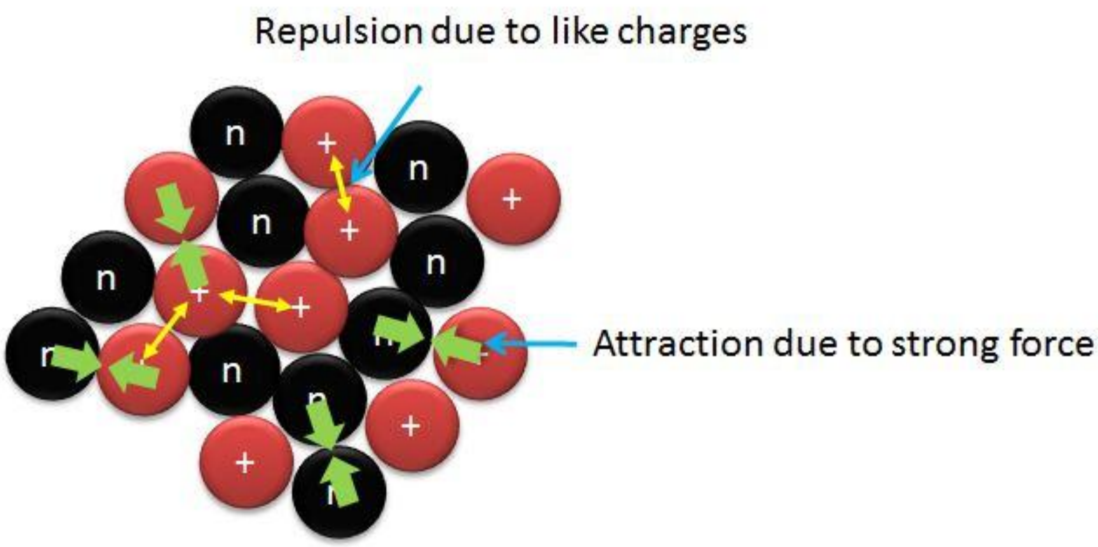

Figure 7 Forces within the nucleus

The protons and neutrons are called **nucleons**. Both feel the strong force. The **strong** force has these features:

- Electrostatic repulsion between 2 protons has a value of about 200 N.
- This means the protons would move apart with an acceleration of 1.2×10^{29} m s^{-2}.
- Therefore, the strong force must pull nucleons with at least that kind of force.
- It has a very short range, about 3 femtometres (3 fm = 3×10^{-15} m).

This is shown on the graph showing the force between two protons:

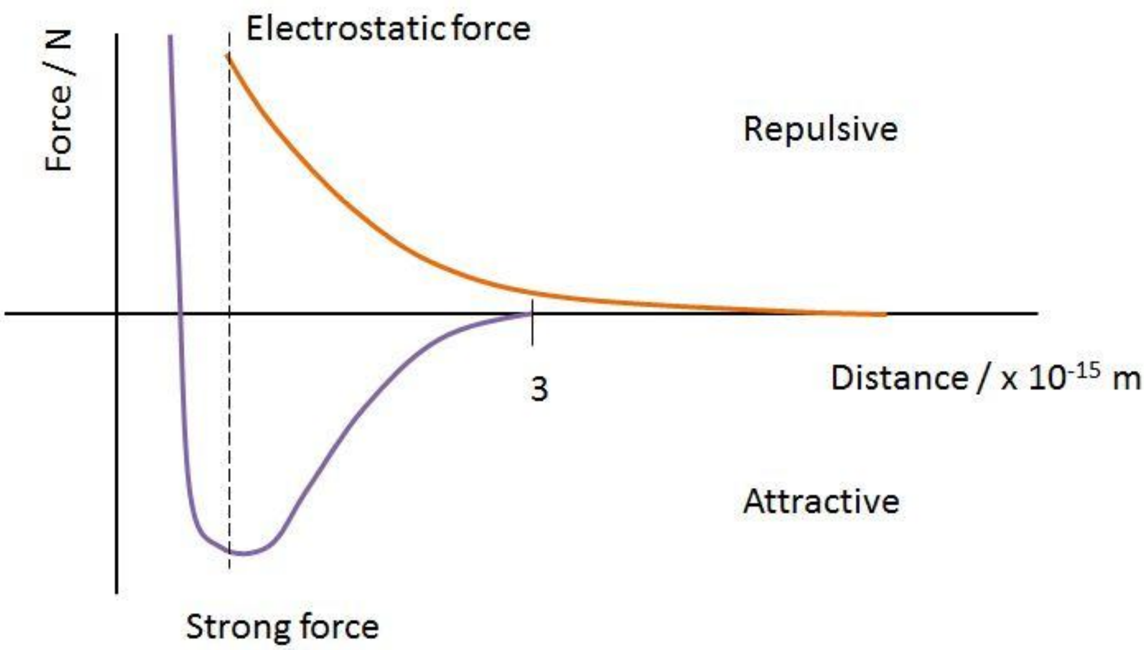

Figure 8 Force-distance graph for two nucleons

From this graph we can see that:

- The repulsive electrostatic force is equal in value but has the opposite direction to the attractive strong force.
- This happens at about 1 fm.
- The strong force is zero at 3 fm.
- Therefore, if the distance from the centre is more than 3 fm, there is an overall repulsive force, and the two protons will fly apart.

Neutrons help to bind the nucleus together by the strong force, but the numbers of neutrons and protons have to be right. Otherwise, the nucleus is unstable. The more protons there are, the more neutrons are needed to keep the nucleus stable. There is a limit, which is reached when the proton number is 82, i.e. lead:

$$^{208}_{82}Pb$$

Lead is the largest stable nucleus. To hold the 82 protons of the lead nucleus together, 126 neutrons are needed.

2.022 Unstable Nuclei

Most isotopes have the right numbers of protons and neutrons to be stable. However some isotopes are **unstable**. This results from the nucleus:

- being too big.
- having too many neutrons.
- having too many protons (rare).

This activity will show you how the neutrons hold together the nucleus to keep it stable: https://phet.colorado.edu/en/simulation/build-an-atom

Radiation is the process by which an unstable **parent** nucleus becomes more **stable** by **decay** into a **daughter** nucleus by emitting **particles** and/or **energy**. The basic form of radioactive decay can be summed up in this diagram:

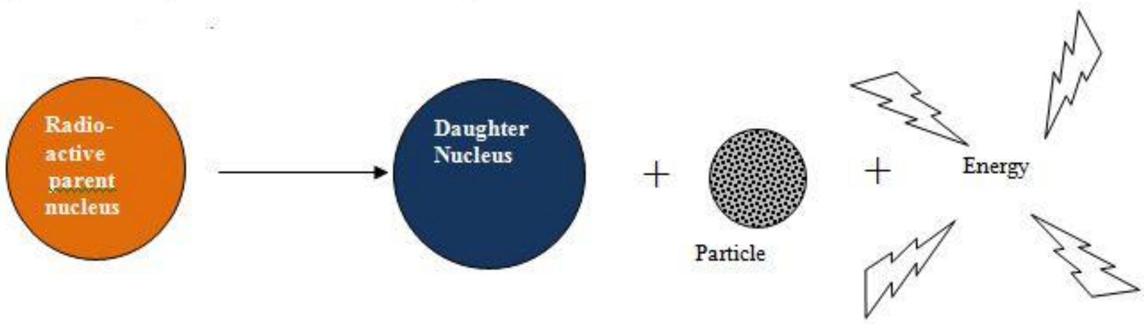

Figure 9 Unstable nucleus loses energy by radiation

The decay can consist of several steps. The unstable nucleus decays to another nucleus of a different atom by a process called **transmutation**. If the new nucleus is unstable, it will decay again. This is known as a **decay chain**. There may be several steps, some of which last a very long time indeed, or can be very short. Some elements have a decay time of thousands of millions of years. In others the decay time can be microseconds. Whichever, the process is entirely **random**. If you watch an individual nucleus, the decay may occur in 10 seconds, or several million years. There is nothing whatever you can do to speed up the process.

Elements have different **isotopes**. An element and its isotope have:

- The same number of protons (and electrons)
- Different numbers of neutrons.

If the isotope is unstable, it is **radioactive** and is called a **radioisotope**.

The radioactive decay is measured by the number of **counts per second** or **disintegrations per second**. A computer can act as a rate-meter and store the results. It will also plot a graph. The unit for counts per second is the **Becquerel** (Bq):

1 Bq = 1 count per second

2.023 Radiation

There are three kinds of radiation:

- **Alpha** – a helium **nucleus**.
- **Beta** – a high-speed **electron**.
- **Gamma** – an **electromagnetic** radiation of wavelength about 10^{-14} m.

These kinds of radiation can be emitted individually or in any combination, depending on the type of isotope that is emitting the radiation. Often when an alpha particle is emitted the nucleus is **excited** and releases the excess energy in the form of a **gamma ray** or gamma photon.

When specimens of radioactive isotopes decay, they do so entirely **randomly**. There is no pattern whatsoever, and the rate of decay is not affected by temperature or other physical factors, or chemical reactions. This means you cannot speed it up by hitting the material, heating it strongly, or reacting it with strong acids.

The table helps us to compare the properties of radiation:

Radiation	Description	Penetration	Ionisation	Effect of E or B field
Alpha (α)	Helium **nucleus** 2p + 2n $Q = +2\,e$	Few cm air Thin paper	Intense, about 10^4 ion pairs per mm.	Slight deflection as a positive charge
Beta (β)	High speed electron $Q = -1\,e$	Few mm of aluminium	Less intense than a, about 10^2 ion pairs per mm.	Strong deflection in opposite direction to α.
Gamma (γ)	Very short wavelength em radiation	Several cm lead, couple of m of concrete	Weak interaction about 1 ion pair per mm.	No effect.

We will look at the mechanisms of production of alpha and beta radiations later.

2.024 Radiation Protection

We need to be aware that elements with unstable nuclei can be harmful to living organisms.

- Alpha particles are **intensely ionising**. The good news is that they are stopped by a few cm of air or by the **skin**. The bad news is that if you ingest an alpha emitter, the radiation quickly will macerate the DNA of living cells, such as the lining of the intestines or lungs.
- Beta particles can penetrate the body but are stopped by a few mm of Aluminium. They are less damaging than gamma rays or alpha particles. They are weakly ionising. Some **medical tracers** are radioisotopes that are beta emitters
- Gamma rays are considered the most dangerous form of radiation, as they are very penetrating. They are **attenuated** by several centimetres of lead but not stopped completely. Therefore, they can pass easily through our bodies. Surprisingly, they cause very little **ionisation**, which causes genetic damage, and are not absorbed very efficiently by DNA, so quite a long exposure to gamma rays is needed to destroy DNA completely. However random damage can be done by smaller doses. It can be repaired by the cell's repair mechanisms, but mis-repair can cause mutations, which can lead to cancer. Intense radiation can mess up DNA sufficiently to cause radiation sickness. This can of course apply to other radiations as well.

People working with radioactive materials must take precautions to ensure their safety, such as:

- Not touching the material directly but handling it with tongs.
- Washing their hands after each job handling radioactive materials.
- Wearing lead aprons.
- Wearing a film badge.

Figure 10 A Film Badge

Work with highly radioactive materials is carried out remotely behind walls that are 2 metres thick.

In a school physics lab, the sources are VERY weak, but you must always follow the rules in their handling. Students under 16 are not allowed to handle radioactive materials.

2.025 Possible modes of decay for unstable nuclei

Alpha radiation (α) mostly comes from heavy nuclides with proton numbers greater than 82, but smaller nuclides with too few neutrons can also be alpha emitters. The term Q stands for the **energy**. The animation shows the idea:

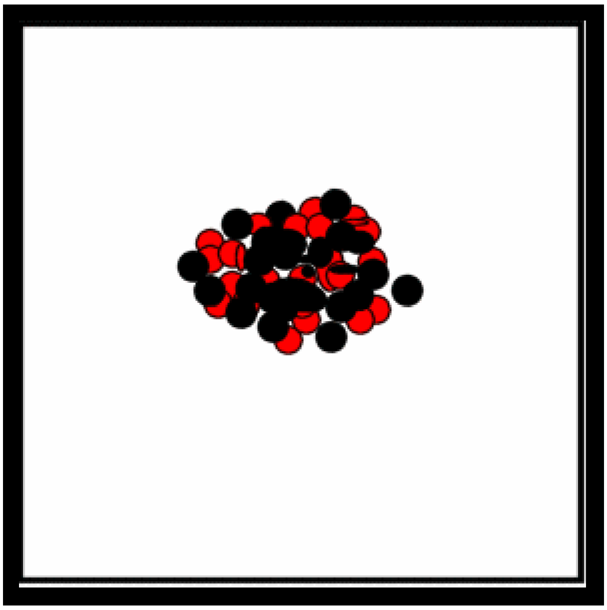

Figure 11 Animation to show the emission of an alpha particle

The general decay equation is summarised below.

$$^{A}_{Z}\mathrm{X} \longrightarrow {}^{A-4}_{Z-2}\mathrm{Y} + {}^{4}_{2}\mathrm{He} + \mathrm{Q}$$

Figure 12 General equation for alpha decay

We should note the following:

- The alpha particle is a helium **nucleus** (NOT atom).
- Energy is released in the decay. The energy is **kinetic**, with the majority going to the alpha particle and a little going to the decayed nucleus.
- The velocity of the alpha particle is much greater than that of the nucleus.
- The **nucleon number** goes down by 4, the **proton number** by 2.
- A typical alpha decay is:

$$^{228}_{90}\mathrm{Th} \longrightarrow {}^{224}_{88}\mathrm{Ra} + {}^{4}_{2}\mathrm{He} + \mathrm{Q}$$

Figure 13 Decay of thorium by alpha emission

Alpha particles are **intensely ionising**. They smash through air molecules, knocking off electrons as they go. However this reduces the kinetic energy, so that in the end they stop. Then they pick up a couple of free electrons to become helium atoms. To collect an appreciable sample of helium from an alpha emitter would take a very long time.

Neutron rich nuclei tend to decay by **beta minus (β-) emission**. The beta particle is a **high-speed electron** ejected from the nucleus, NOT the electron clouds. It is formed by the decay of neutrons, which are slightly more energetic than a proton. Isolated protons are stable; isolated neutrons last about 10 minutes.

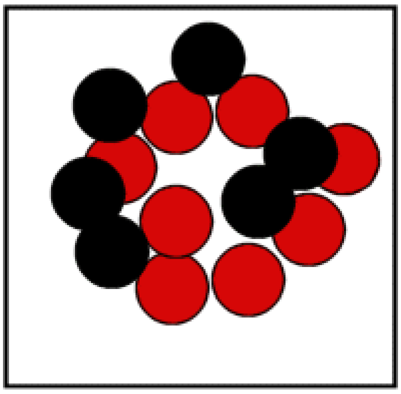

Figure 14 Animation that shows beta minus decay

Watch how the neutron in *Figure 14* suddenly emits an electron (blue) and the electron anti-neutrino (black), turning into a proton.

The neutron, having emitted an electron, is converted to a proton, and this results in the proton number of the nuclide going up by 1. **A new element is formed**. The reaction at the nucleon level is:

$$^{1}_{0}\mathrm{n} \longrightarrow {}^{1}_{1}\mathrm{p} + {}^{0}_{-1}\mathrm{e} + {}^{0}_{0}\bar{\nu}_e + \mathrm{Q}$$

Figure 15 General equation for beta minus emission

Notice that as well as the neutron (n) and the proton (p), the beta particle is represented as an electron (e^-). The strange symbol ν_e ('noo-bar e') is a strange little particle called an **electron antineutrino**. (Note: The sign for an antiparticle is usually the particle symbol with a bar over it. It is not possible to do this satisfactorily in this text-editor, so in the text, I will show it as white font highlighted in black. Therefore X-bar will be shown as X. The equations are pictures produced by a graphics equation editor.)

$$\overline{\nu_{\varepsilon}}$$

Figure 16 Equation symbol for an electron antineutrino

Observations of beta minus decay led to the concept of the neutrino. Enrico Fermi (1901 - 1954) noticed that when a nucleus ejected a high-speed electron, it did not recoil in the opposite direction to the path of the electron. It recoiled at a slight angle. Conservation of momentum rules suggested that there must have been a third very tiny particle, which he called the neutrino (neutral little thing).

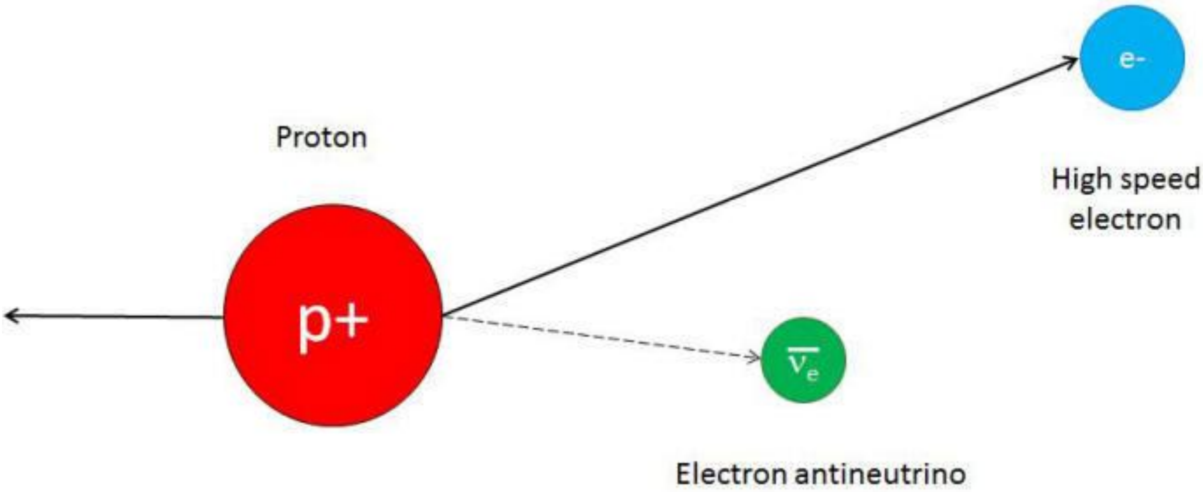

Figure 17 Emission of the electron antineutrino and electron from a proton

Later it was called the electron neutrino (as it was associated with an electron). However, the use of **quantum numbers** showed that it must be an **electron anti-neutrino**.

The general equation for b- decay is:

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

Figure 18 General Equation for beta minus decay

A typical decay is:

$$^{29}_{13}\mathbf{Al} \longrightarrow {}^{29}_{14}\mathbf{Si} + {}^{0}_{-1}\mathbf{e} + {}^{0}_{0}\bar{\nu}_e + \mathbf{Q}$$

Figure 19 Equation for beta minus decay of Al-29

Notice that:

- The nucleon number remains the same.
- The proton number goes up by 1.
- The beta particle is created at the instant of the decay.
- The antineutrino is very highly penetrating and has a tiny mass. It is very hard to detect.
- A precise amount of energy is released, according to the nuclide.
- That energy is shared among the nucleus, the electron and the antineutrino.

2.026 Beta Plus decay

There is another kind of decay, **beta plus** decay. In this case, the nucleus has too many protons and gets rid of the excess charge by turning a proton into a **neutron**. This is rare in nature, but proton-rich unstable nuclei are found in reactors.

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

Figure 20 A general equation for beta plus decay

The beta plus decay spits out a positively charged particle called a **positron**. The positron is an **anti-particle** to the electron. It has the same mass, but the opposite charge to the electron. The other particle emitted is an **electron neutrino**.

Radioactive nuclides often decay to other unstable nuclides. There may be several of these that happen until a stable nuclide is formed. The term used for one of these multiple-step decays is a **radioactive decay series**.

The particles emitted by radioactive nuclei are NOT in themselves radioactive.

The **helium nuclei** of alpha particles are very stable. Once they pick up electrons, they become **helium atoms** which are unreactive.

The electrons in beta minus radiation are normal electrons.

2.027 Energy lost in Radioactive Decay

Each time a particle is ejected from the nucleus, energy is transferred. Most of this is in the kinetic energy of the ejected particle. We will assume that all the energy in the particle is kinetic. Some is left as energy in the nucleus, which is lost as a gamma ray. We will study this more in Nuclear Physics.

Consider a particle that has been ejected from a nucleus. It has energy E_{k}. We know that the kinetic energy is given by:

$$E_{\mathrm{k}} = \frac{1}{2}mv^2$$

The particle will hit any atoms in the way, ionising them.

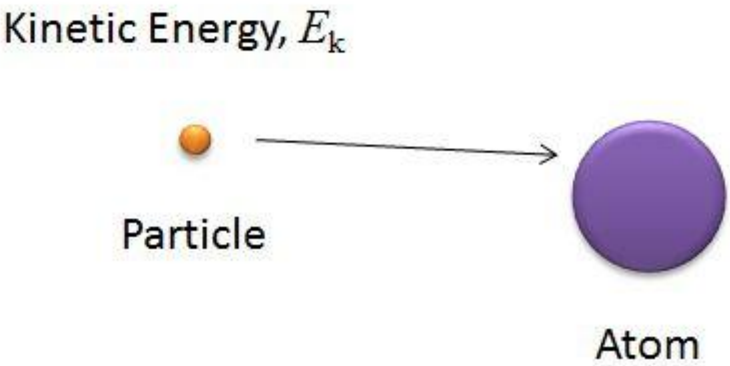

Figure 21 Particle about to strike an atom

This means that an electron is knocked off. This electron will have picked up a certain amount of energy, which we will call E_1. The idea is shown in *Figure 22*.

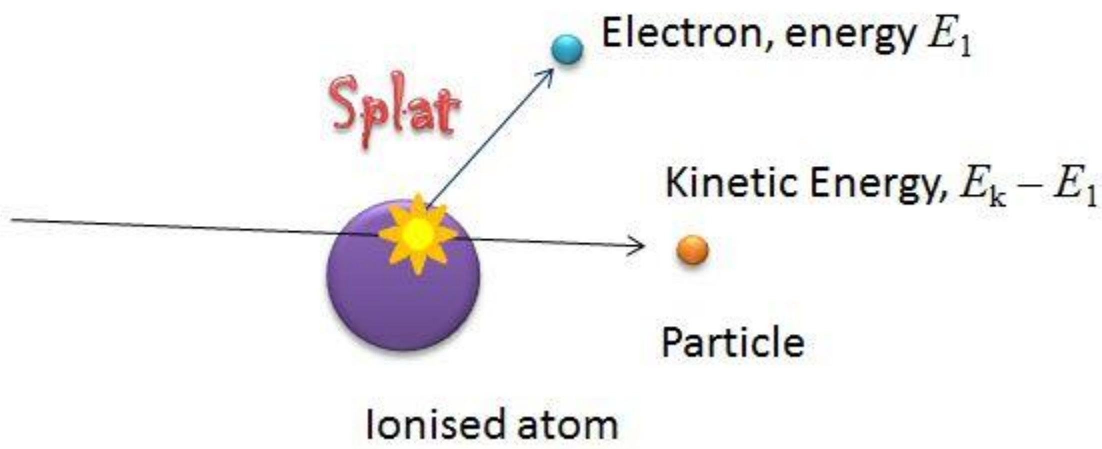

Figure 22 Ionisation of an atom by another particle

The particle continues on its journey, having lost a certain amount of energy. Its new kinetic energy, E' ("E-prime") is given by:

$$E' = E_k - E_1$$

We assume that:

- the space between atoms is empty, so no energy is lost.
- it loses the same amount of energy, E_1 in every collision, we can work out the number of collisions, N, by:

$$N = \frac{E_k}{E_1}$$

2.028 Modelling Radioactive decay

We use the term **model** to describe a miniature train or aeroplane. We can also use it to describe a model girl or boy in the fashion industry. In the context of a model farm, it means a technique or method.

A **model** in physics is a way of making something complicated simpler to understand or using a mathematical technique to show the concept.

A simple way of modelling radioactive decay is **using dice**. We take 100 dice in a container and throw them onto a tray. We pick out those that show a 6 and put those to one side. These represent the decayed nuclei. We count these and take them away from 100 to give us the undecayed nuclei. We then put the dice that don't show a 6 back into the container and repeat the process. You then plot a graph for your results. It shows a rough exponential decay shape, but not very good. If we use the whole class data, the graph looks a lot better as in *Figure 23*.

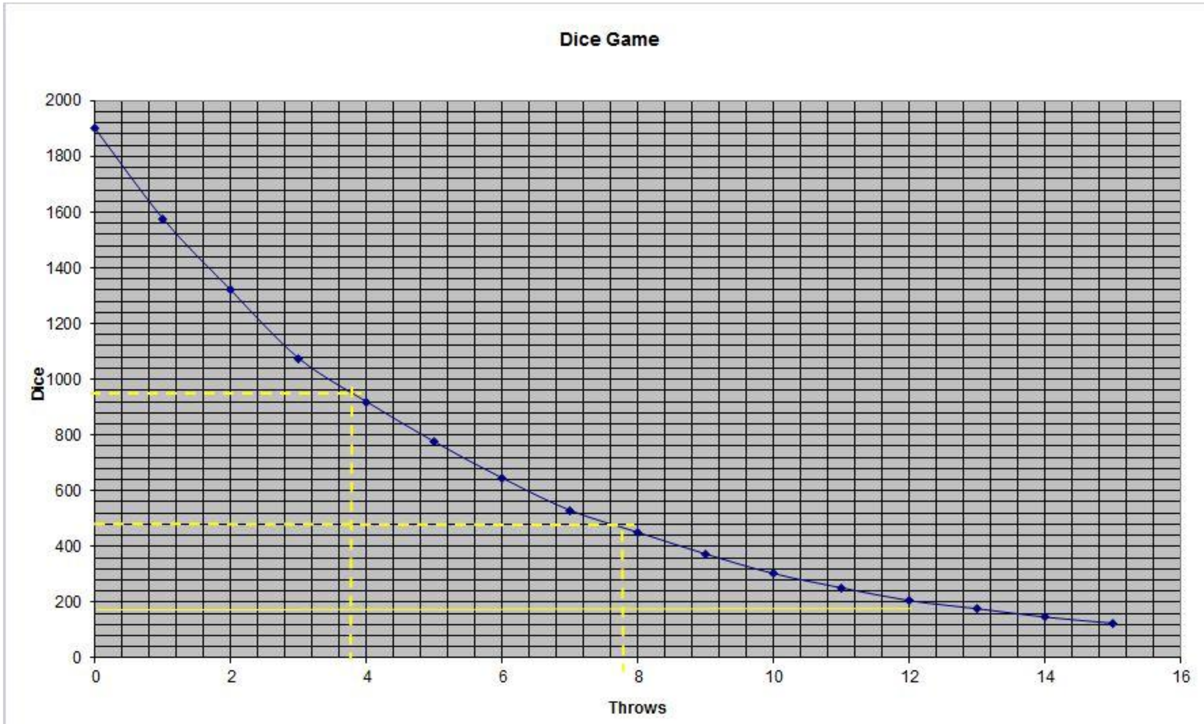

Figure 23 Typical whole class results for modelling radioactive decay with 100 dice.

The half-life is about 3.75 throws. Yes, I know you can't have 0.75 of a throw, but radioactive decay is a statistical phenomenon. To get a perfect exponential decay, we need many thousands of throws. In a small sample of atoms, we might have 10^{20} nuclei.

We can model radioactive decay using a computer program at https://doctor-pasquale.com/simulations/halfLife.html

You can identify a radioactive decay series and analyse the types of decay taking place that leads to the series.

You will find the following website useful for a real alpha decay:

https://doctor-pasquale.com/simulations/halfLife.html

It is important to understand the following about radioactive decay:

- It is entirely a **random** process.
- The half-life is a property of the atom, or **nuclide**.
- A **nuclide** is a combination of a **specific number of protons and neutrons**.
- The half-life of a particular nuclide is exactly the same regardless of whether the nuclide is an element or a compound.
- No two nuclides share exactly the same half-lives.
- The half-life cannot be altered by chemical reactions, however fierce.
- The half-life cannot be altered by even the most extreme physical conditions.

These principles apply regardless of whether the decay is alpha, beta, or gamma.

Tutorial Questions for 2.02

2.02.1

What element is the nucleus in *Figure 7* of? Write it out in isotope notation.

2.02.2

Is this equation balanced in *Figure 13*? Explain your answer.

2.02.3

What is the balanced nuclear equation for the following decays?

(a) emission of a beta- particle from oxygen 19

(b) emission of an alpha particle from polonium 212

(c) emission of a beta + particle from cobalt 56

Proton numbers O – 8, F – 9, Fe – 26, Co – 27, Pb – 82, Po – 84

2.02.4

Alpha and beta particles lose about 5×10^{-18} J of kinetic energy in each collision they make with an air molecule. An alpha particle makes about 10^5 collisions per cm with air molecules, while a beta particle makes about 10^3 collisions. What is the range of an alpha particle and a beta particle if both start off with an energy of 4.8×10^{-13} J?

Tutorial 2.03 Electromagnetic Radiation	
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2.031 Electromagnetic Waves

The **electromagnetic spectrum** is a family of waves that have the following properties:

- They are transverse.
- They all travel at 300 million m s^{-1} (3×10^8 m s^{-1}) in a vacuum.
- They can travel in a vacuum, so need no material to travel in.

They are made up of an electric field and a magnetic field at 90° to each other. The **electric field** (E) and the **magnetic field** (B) are always **in phase** (in step) with each other.

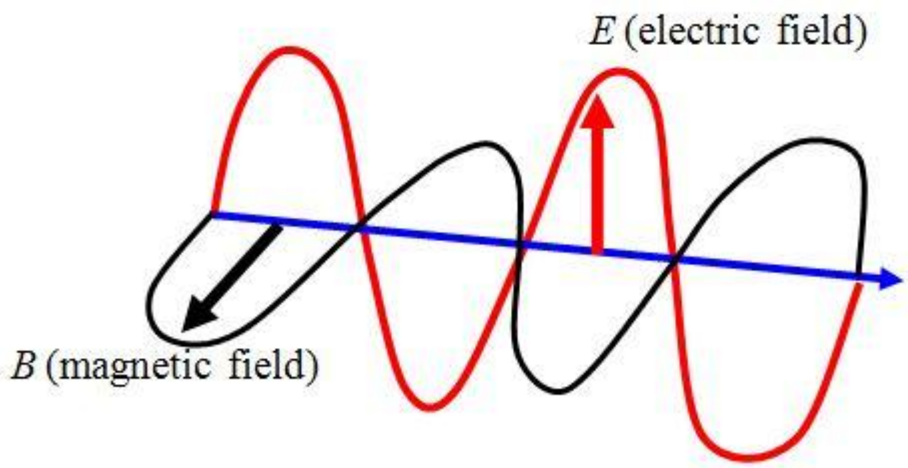


Figure 24 Diagram of an electromagnetic wave

The main parts of the electromagnetic spectrum are shown in *Figure 25*.

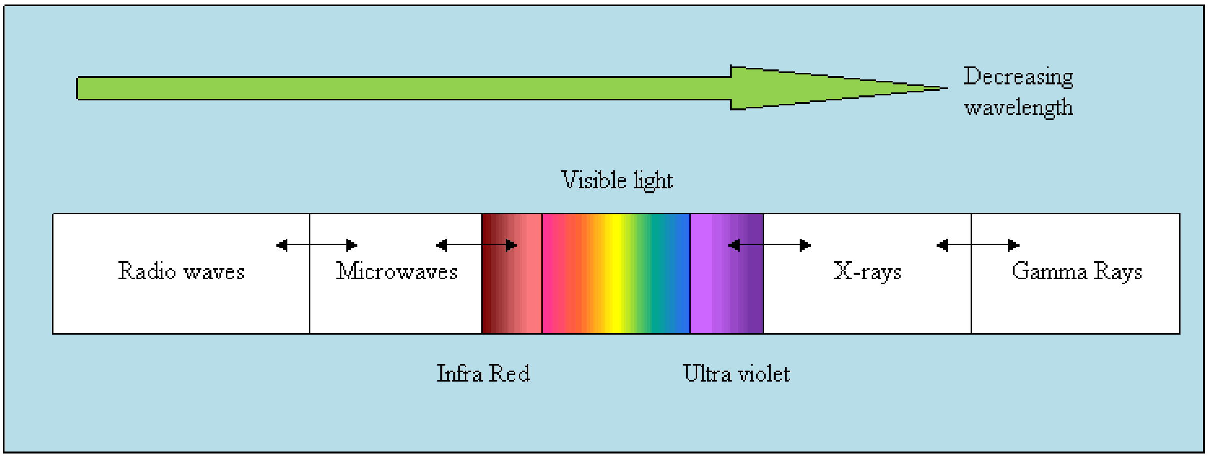


Figure 25 Main regions of the electromagnetic spectrum

Figure 26 shows typical wavelengths:

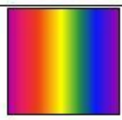
Type	Radio	Micro-waves	Infra-red	Visible	Ultra Violet	X-rays	Gamma rays
Wavelength	> 10 cm	10 cm – 1 mm	1 mm – 700 nm	700 nm - 400 nm	400 nm – 1 nm	10^{-10} m	10^{-14} m
							γ

Figure 26 Typical wavelengths for electromagnetic radiation.

Infra-red can be detected using a **charged-coupled device**. Digital cameras can detect near (short wavelength) infra-red. The halogen hot plate has a "halo" around it as shown in *Figure 27*.

Figure 27 Infra-red can be detected by digital cameras

You can also see infra-red LEDs flashing through a digital camera.

All objects can absorb or emit radiation. **Infra-red cameras** pick up radiation emitted by hot objects. This allows wildlife cameramen to film animals at night. The animals cannot see infra-red, so are not disturbed by bright infra-red lights. The images are in black and white; colours cannot be seen.

UV light is detected using **photomultipliers**, often known as tubes. **Phosphor** screens in the photomultipliers **fluoresce** with visible light when exposed to UV light, and this can be detected with a charge-coupled device.

Light shows wave behaviour:

- It refracts and reflects.
- It is diffracted.
- As a transverse wave, it can be polarised.

Like all waves, EM waves follow the **wave equation**:

$$\lambda = \frac{c}{f}$$

The symbol λ is *lambda*, a Greek letter 'l'. It is the physics code for **wavelength**, measured in metres.

Speed of light (3.0×10^8 m s^{-1}) is given by the code c, while f is the **frequency** (Hz). Light waves are often given in **nanometres** (nm) where 1 nm = 1×10^{-9} m.

2.032 Photons

Physicists now believe that light travels in packets of waves called **photons**. (We will look at the evidence for this in the photo-electric effect.) Each photon is a train or burst of waves. Photons are given out when **charged particles** lose energy. These travel in **random directions** from a light source. Once they have left the light source, the photons travel in **straight lines** until reflected or refracted.

We can represent a photon like this (*Figure 28*).

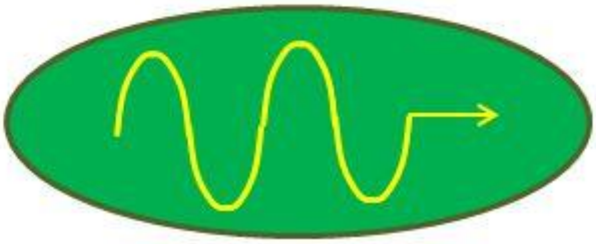


Figure 28 Representation of a photon

Photons are **pure energy**. They have **zero mass**, which means that they can travel at the speed of light, 3.0×10^{8} m s^{-1}.

The energy of each photon is given by the simple equation:

$$E = hf$$

- E – energy per photon (J);
- h – Planck's constant, 6.63×10^{-34} J s (joule-seconds, NOT joules per second)
- f – frequency (Hz)

2.033 Evidence for Photons

Consider an old-fashioned black and white picture taken on a film. We take the picture using a negative. We then expose photographic paper to the negative using an enlarger. We make a negative of a negative which makes a positive. We then develop the image using chemicals. A very short exposure shows random dots of silver.

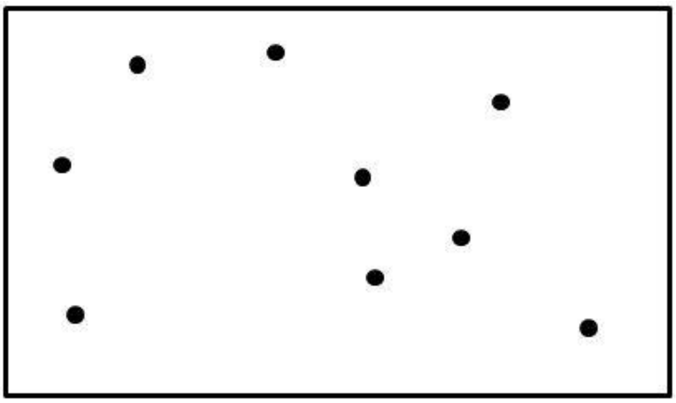


Figure 29 Random photons depositing sliver grains on a photographic image.

A longer exposure shows the picture getting darker and showing more detail as more grains of silver are deposited. Each random grain of silver is deposited by a photon of light coming from the bulb of the enlarger. We can see this on this in the picture of a photographer's test strip (*Figure 30*).

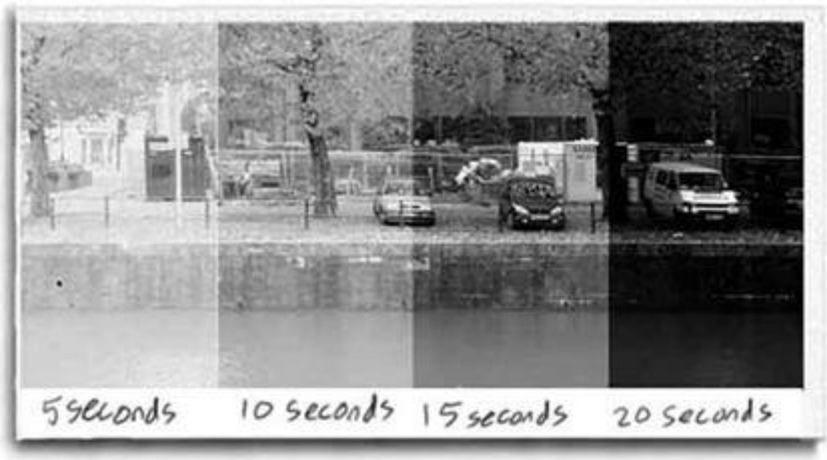


Figure 30 A photographer's test strip

The same random effect can be seen with the CCD of a modern digital camera. The image (*Figure 31*) shows a very bad picture taken in low light conditions.

Figure 31 This picture was taken in low light conditions and has very poor detail.

The image is very grainy and lacks detail. This isn't so obvious with the small size of the picture, but when enlarged, it is dreadful.

Wavelengths are often given rather than frequency, so we have to convert to frequency using:

$$\lambda = \frac{c}{f}$$

It doesn't take a genius to see that this relationship can be substituted to give us:

$$E = \frac{hc}{\lambda}$$

Worked Example What is the photon energy of red light of wavelength 600 nm?
Answer Use: $$E = \frac{hc}{\lambda}$$ $E = \dfrac{6.63 \times 10^{-34}\ \text{J s} \times 3 \times 10^{8}\ \text{m s}^{-1}}{600 \times 10^{-9}\ \text{m}} = \mathbf{3.32 \times 10^{-19}\ J}$

2.034 Power of a Beam of Light

If we have n photons, each of energy E, passing a particular point every second, we can easily work out the **power** P (energy per second).

$$P = nhf$$

If we know the power of a laser beam, we can work out many photons it gives out every second.

Figure 32 A typical school laser

Worked example How many photons are squirted out by a laser every second, if its wavelength is 620 nm, and its power is 150 mW?

Answer

Use:

$$E = \frac{hc}{\lambda}$$

$E = (6.63 \times 10^{-34}\ \text{J s} \times 3 \times 10^{8}\ \text{m s}^{-1}) \div 620 \times 10^{-9}\ \text{m} = 3.21 \times 10^{-19}\ \text{J}$

Power of the laser = 0.15 W

Number of photons per second = $0.15\ \text{W} \div 3.20 \times 10^{-19}\ \text{J} = 4.7 \times 10^{17}\ \text{s}^{-1}$ (2 s.f.)

An account of how the laser works can be found in Quantum Physics.

Remember to convert MHz to Hz?

Tutorial 2.03 Questions

2.03.1

What evidence is there that light is a wave?

2.03.2

(a) What is the frequency of radio waves of wavelength 247 m?

(b) An electromagnetic radiation has a frequency of 2.0×10^{13} Hz. What is its wavelength? What region of the electromagnetic spectrum is this?

Give your answers to an appropriate number of significant figures.

2.03.3

What do you understand by the term photon?

2.03.4

Write down the formula that links photon energy with frequency. Explain each term and give the correct units.

2.03.5

Aeroplanes approaching to land at Leeds Bradford Airport (Yeadon Aerodrome, EGNM) are guided in to the runway by a beam of radio waves transmitted at a frequency of 110.90 MHz.
(a) What is the wavelength of the radio waves?
(b) What is the energy per photon?
(c) If the transmitter has a power of 100 W, how many photons are given out every second?

2.03.6

At the start of the Twentieth Century, most physicists were convinced that light was a wave. However, there was evidence that light was a particle.

Outline the evidence that suggests that light is a wave, and that light is a particle. Discuss the model that physicists use to explain this apparent contradiction.

Tutorial 2.04 Fundamental Forces

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2.041 What is a fundamental force?

There are four **fundamental forces** that are responsible for all **phenomena** (things that happen) in physics, and all the forces that we can name can be explained in terms of these fundamental forces. They are **gravity**, **electromagnetic force**, **strong nuclear force**, and the **weak nuclear force**.

2.042 Gravity

Gravity is always attractive. It is never repulsive. It is a property of bodies with mass but is very weak indeed. The only reason we feel gravity at all is that the Earth is a huge object, of mass 6×10^{24} kg. Gravity is responsible for the Universe the way we see it today.

At the nuclear level, **gravity is far too small** to be responsible for nuclear phenomena. It is thought to be mediated by a particle called the **graviton**, but such a particle has never been observed. Since the range is infinite, and stars and planets are attracting each other all the time, presumably the Universe must be crawling with the little brutes.

2.043 Electromagnetic Force

Electromagnetic forces are observed in the interactions between **atoms**. We know how atoms have a positively charged nucleus surrounded by a cloud of negatively charged electrons. Molecules are bound together by electrical forces, which have an infinite range, and can be attractive or repulsive. The mechanisms for chemical reactions can be explained in terms of the electromagnetic force at the atomic level.

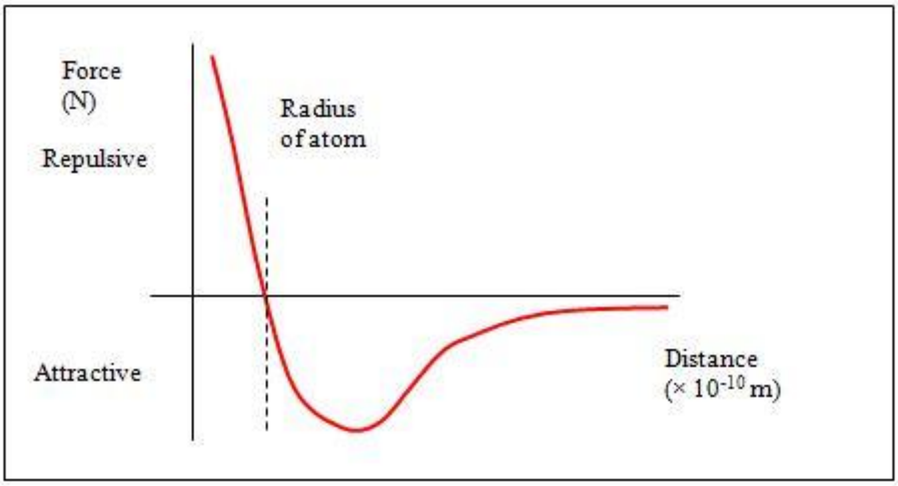


Figure 33 Graph showing the electromagnetic force between two atoms

This graph (*Figure 33*) tells us that if we pull two atoms apart, there is an attractive force from the bonds that pulls the atoms back together. If we squash the two atoms together, there is a large repulsive force that pushes them apart. At a distance that is about the radius of an atom, the two atoms will experience zero force.

The electromagnetic force is transferred or mediated by the **virtual photon**. This means you can't see it in action (in other words, you don't get flashes of light from your bottom when you sit down). If you see the photon, it means it's not being involved in the electromagnetic force. Virtual particles have only a very short lifetime.

2.044 The Strong Nuclear Force

We know that the positively charged nucleus is very tiny, about one ten thousandth the size of an atom. We also know that positives repel. We can do a calculation on two positive charges to find that a force of about 200 N exists between them. So why does the nucleus not fly apart? There is a force that stops this, the **strong nuclear force**. It is very short range, in the order of 10^{-15} m, or 1 femtometre.

We can draw a very similar graph to the one above to show what happens when we pull two nucleons apart or squash them together. See *Figure 34*.

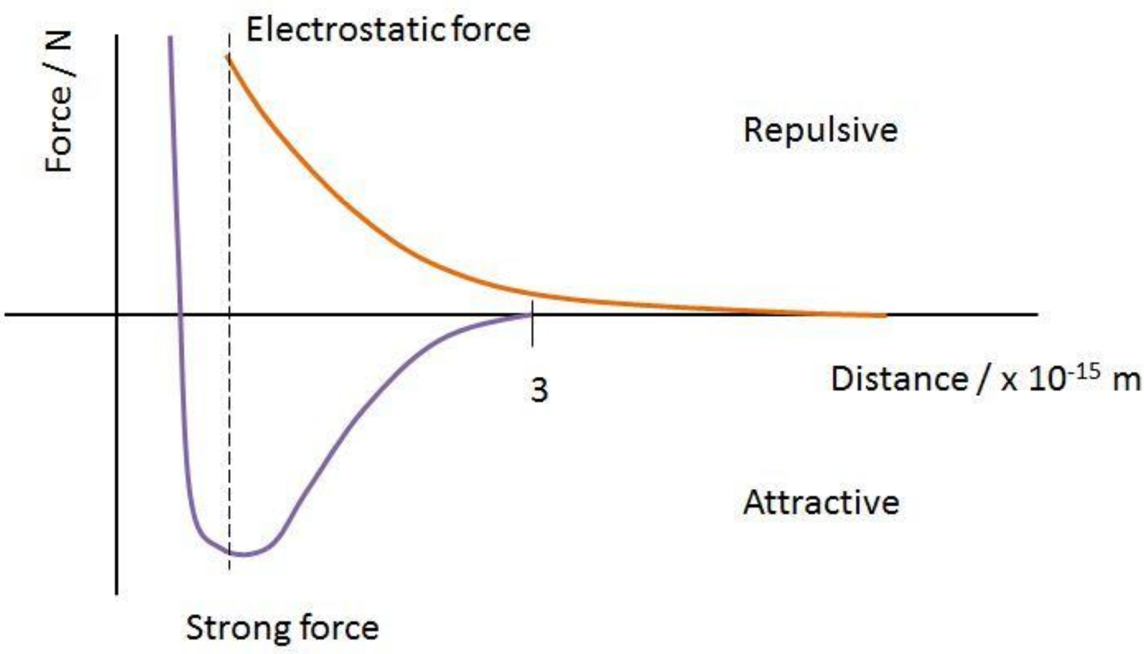


Figure 34 Force distance graph showing the strong force acting on nucleons

The strong force is mediated by **gluons** which bind the nucleons together. All hadrons feel the strong force.

2.045 The Weak Nuclear Force

There is another force that is only found within the nucleus, the **weak nuclear force**, which is responsible for **beta minus decay**. The weak force has a very short range, about 10^{-18} m. In beta decay, things happen that cannot be explained by the action of the electromagnetic force, gravity, or the strong force. There is a theory that it's actually another form of the electromagnetic force. The weak force is poorly understood.

The weak force is mediated by the **W** and **Z bosons**:

- W- mediates the beta minus decay, and its variants which we will look at later.
- W+ mediates the beta plus decay.
- The role of the Z boson is not well understood.

2.046 Comparing the forces

We can sum the forces up in this diagram (*Figure 35*).

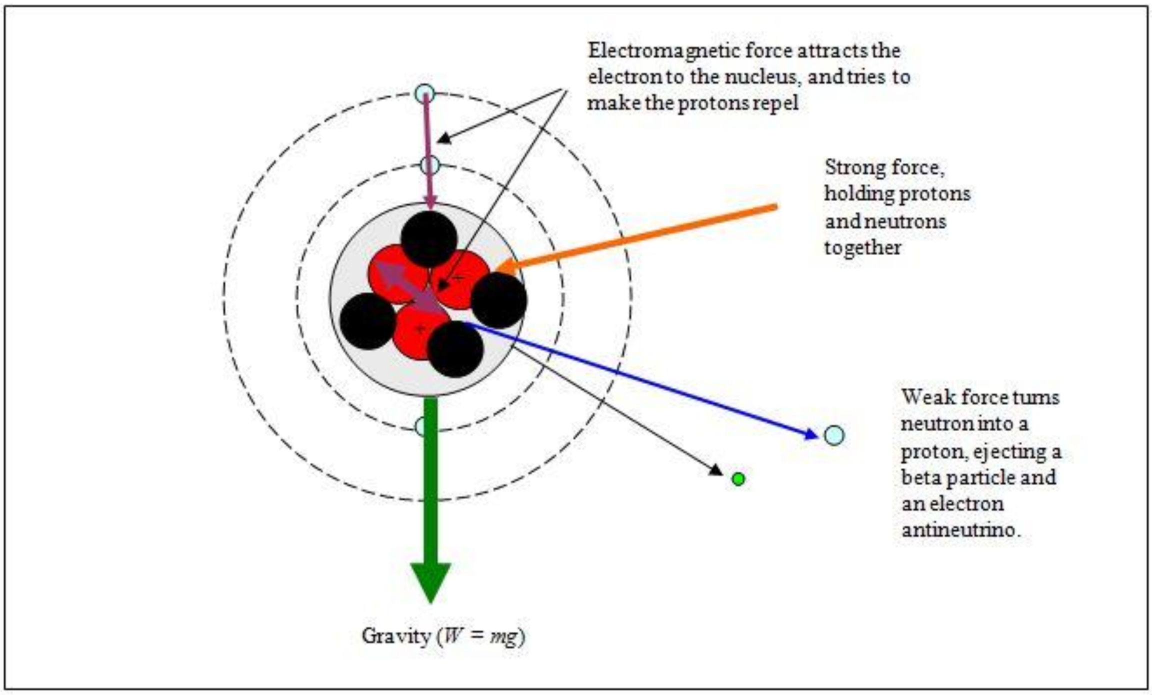


Figure 35 Fundamental Forces acting in the atom

The table shows the strength of the forces relative to gravity:

Force	***Acts on***	***Range (m)***	***Relative strength***	***Mediated by***
Gravity	All objects with mass	Infinite	1	Graviton
Electromagnetic	Charged objects	Infinite	10^{36}	Photon
Strong	Quarks and nucleons	1×10^{-15}	10^{38}	Gluon
Weak	Quarks	1×10^{-18}	10^{25}	W+, W-, and Z Bosons

2.047 Exchange Particles

All forces are mediated by **exchange particles** which carry **momentum** and **energy** from one particle to the other. The simplest model to understand their action is like this:

- The particle borrows mass from the first particle and passes it to the second particle.
- The exchange particle has a very brief existence.
- The second particle returns the mass to the first by another exchange particle.

Each particle in this model is represented by a boy on a skateboard. Particle A throws a ball to Particle B who catches it. Since **momentum** has to be conserved, Particle A moves to the left as he throws the ball. Particle B moves to the right as he catches the ball. So the two boys move apart. See *Figure 36*.

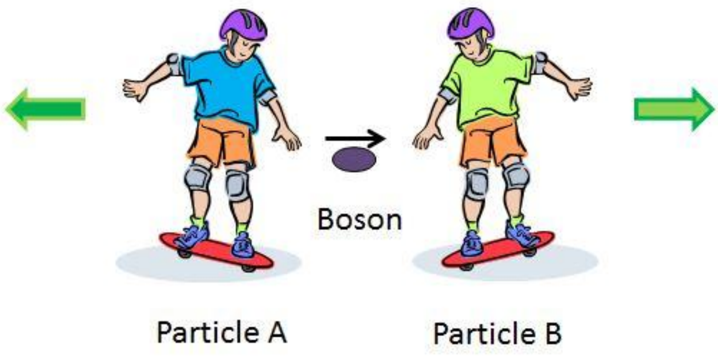


Figure 36 Modelling a repulsive force

This models a **repulsive** force.

If we want to model an **attractive** force, we use the idea of a boomerang. See *Figure 37*.

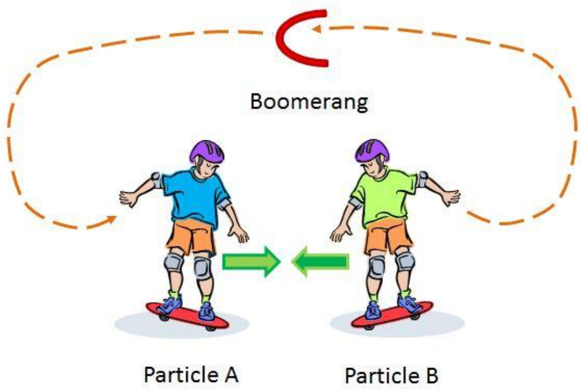


Figure 37 Modelling an attractive force

Particle B throws the boomerang towards his mate, Particle A. As he throws it, conservation of momentum dictates that he must move to the left. Particle A catches it and the boomerang transfers momentum, moving Particle A to the right. The two boys move together.

This may sound strange, but:

Mass and energy are interchangeable at the sub-nuclear level.

2.049 Boson

All exchange particles are **bosons**. Not all bosons are exchange particles. **Mesons** are bosons but are not exchange particles. We will look at mesons in a later tutorial. Exchange particles are sometimes called **gauge bosons**. There is more about this in Tutorial 11.

There is another family of particles called **fermions**. The fermions include leptons, quarks, and baryons. The division is the result of a mathematical theory, not through direct observation. However, observations have supported what the theory has predicted.

Particles have the quantum numbers of **spin**. Some particle models have the idea that the particles are tiny spinning objects. Bosons have a **whole number value** of spin. Fermions have half values of spin, for example, 1/2, 3/2, and 5/2. This is beyond what you need to know.

Bosons are allowed by quantum theory to do the **same thing together**. Photons are allowed to do exactly the same thing, which is why a laser can make photons march precisely in step. This results in a very narrow beam of intense light. Fermions are not allowed to do the same thing at the same time. Therefore, two electrons are not allowed to be in the same orbit at the same time (the Pauli Exclusion Principle). Therefore, you can't make a laser from electrons.

The gauge boson properties are shown in the table.

Force	Particle	Rest Energy	Range
Gravity	Graviton	Zero	Infinite
Electromagnetic	Virtual Photon	Zero	Infinite
Strong	Gluon	0.002 eV	3×10^{-15} m
Weak	W+, W-, Z_0	W = 80 GeV Z = 90 GeV	1×10^{-18} m

Note:

- The graviton has not been found.
- The virtual photon is not detected. If it does get detected, it's not acting as a virtual photon.
- Gluon action is quite complicated, using the concept of colour charge. This is not on the syllabus.
- Weak force is very short range indeed, and the particles are massive.
- Rest energy comes from the idea that mass and energy are interchangeable. We will discuss this in more detail in Tutorial 2.05.

2.049 Grand Unification Theories

Physicists have always liked patterns. James Clerk-Maxwell showed that electrical forces and magnetic forces were different versions of the same thing. The question that is exercising physicists at the moment is whether all four fundamental forces are different versions of the same thing. There has been evidence produced to suggest that the electromagnetic and the weak forces are different versions of the same thing, the so-called "**electro-weak theory**".

The driving force behind machines such as the large hadron collider is to reproduce the extreme conditions immediately after the Big Bang, the titanic explosion that is thought to be the start of the Universe. The theoretical physicist, Peter Higgs, proposed some years ago that there was a particle, the **Higgs boson**, that mediated all the fundamental forces. This would prove that all the forces were really one and the same thing, the **grand unification theory**.

Evidence for the existence of the Higgs Boson was discovered at CERN in 2013. It is thought to be a massive particle of rest energy 126 GeV. It required many high energy collisions and interpretation of particle tracks by supercomputers to show evidence of its existence. CERN have published this image (*Figure 38*).

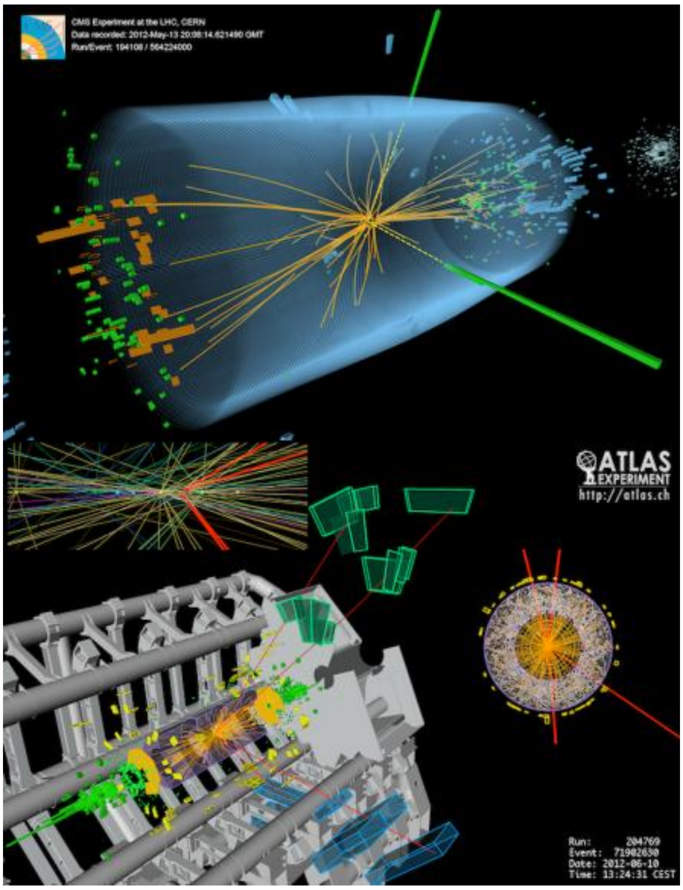


Figure 38 Discovery of the Higgs boson

There is a good website here: https://home.cern/science/physics/higgs-boson

Tutorial 2.04 questions

2.04.1

Two protons experience a repulsive force of about 200 N when they are packed together in a helium nucleus.

(a) Explain why this is the case.

(b) Use $a = F/m$ to work out the acceleration of the protons if they were released.

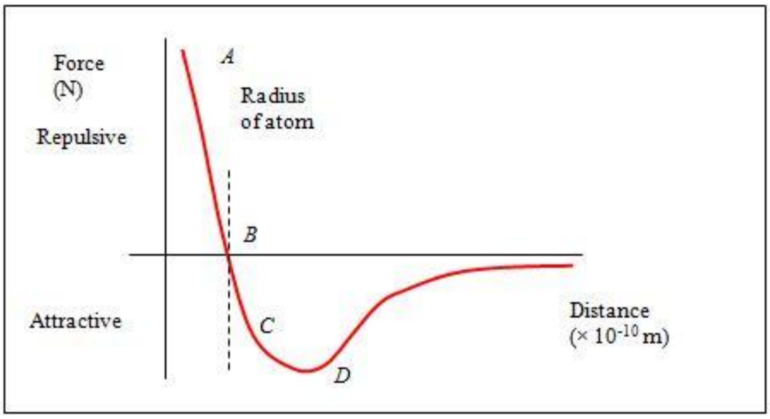
(c) What stops them from flying apart?

2.04.2

What forces are responsible for:	
Chemical reactions	
Attraction between two planets.	
Beta decay	
Holding the nucleus together	

2.04.3

Look at the graph to the below:



(a) What does a positive value of force indicate?

(b) What is happening at point A?

(c) What is happening at Point B?

(d) Which point indicates that a pulling force is being applied?

(e) At which point do the two atoms come apart? Explain your answer.

(f) Which fundamental force is responsible for what we see in this situation?

2.04.4

The diagrams above show how forces behave at the atomic level. Use the model to explain how the electromagnetic force acts between two charge particles that are:

(a) Like-charged.

(b) Oppositely charged.

Tutorial 2.05 Energy, Particles and Antiparticles

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Particle physics is concerned with **fundamental particles**. It used to be thought that protons, neutrons and electrons were the fundamental particles of matter, which could not be broken down into anything smaller. However, it has been found that nucleons are made up of smaller particles, so **nucleons** are now not fundamental. To make sense of quantities involved, we need to look at the units used in particle physics for mass and energy. We have come across them in passing in previous tutorials

2.051 Units in Particle Physics

You will often see some strange looking units when reading about particles. Joules and kilograms are far too big and clumsy at the particle level. In the last tutorial you will have seen that the rest energy of a Higgs boson was 126 GeV.

The main unit you will see is the **electron-volt**. It is not a voltage, but a unit of **energy**. It is the amount of energy that a single electron has when it is accelerated by a potential difference of 1 volt. You have already looked at rest energies in electron-volts in previous tutorials. The electron volt is defined as:

The amount of energy that a single electron has when it is accelerated by a potential difference of 1 volt.

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$

You will also see multiples like keV, MeV, and GeV:

- $1 \text{ keV} = 1000 \text{ eV} = 1.6 \times 10^{-16} \text{ J}$
- $1 \text{ MeV} = 1 \times 10^{6} \text{ eV} = 1.6 \times 10^{-13} \text{ J}$
- $1 \text{ GeV} = 1 \times 10^{9} \text{ eV} = 1.6 \times 10^{-10} \text{ J}$

Worked Example A photon has frequency of 1.0×10^{18} Hz. What is its energy in J and eV?
Answer $E = hf = 6.63 \times 10^{-34}$ J s × 1 × 10^{18} Hz = 6.63×10^{-16} J. $E = 6.63 \times 10^{-16}$ J ÷ 1.6×10^{-19} J eV^{-1} = 4.14 keV

- To convert electron volt (eV) to Joule (J), **multiply** by 1.60×10^{-19} J eV^{-1}.
- To convert Joule (J) to electron volt (eV) , **divide** by 1.60×10^{-19} J eV^{-1}.

2.052 Atomic Mass Unit

You will also see the **atomic mass unit**, **u** (it will not be examined at AS, but will be at A-level):

1 u = 1.661×10^{-27} kg

The atomic mass unit is defined:

Having exactly 1/12th the mass of a carbon-12 atom.

We convert **mass to energy** by using Einstein's simple equation:

$$E = mc^2$$

Where:

- E is the energy (J).
- m is the mass (kg).
- c is the speed of light (3.0×10^8 m s^{-1}).

A particle of 1 u has a rest energy:

$$E = 1.661 \times 10^{-27} \text{ kg} \times (3.0 \times 10^8 \text{ m s}^{-1})^2 = 1.495 \times 10^{-10} \text{ J}$$

Convert this to eV by dividing by 1.6×10^{-19} J eV^{-1}:

$E = 1.495 \times 10^{-10}$ J ÷ 1.6×10^{-19} J eV^{-1} = 933×10^{6} eV = 930 MeV (2 significant figures)

2.053 Rest Mass and Rest Energy

You will also come across an odd expression **rest energy**. At the subatomic level, **mass and energy** are one and the same thing. Mass can be turned into energy, and energy can be made into mass. They are linked by Einstein's famous simple equation:

$$E = mc^2$$

The **rest energy** is expressed in ***MeV***. **Rest mass** is given in *MeV/c*^{2} where *c*^{2} is the square of the speed of light (9.0×10^{16} m^2 s^{-2}). It can be shown that J/ m^2 s^{-2} = kg.

The rest energy (mass) of an electron is 0.511 *MeV/c*^{2} = 9.11×10^{-31} kg.

The rest energy of a muon = $\dfrac{105.7 \times 10^{6} \text{ eV} \times 1.6 \times 10^{-19} \text{ C}}{9 \times 10^{16} \text{ m}^2 \text{ s}^{-2}}$ = 1.88×10^{-28} kg

In this unit we will talk about **rest energy**, but it's the same as **rest mass**. In some syllabuses, the rest mass is used, so the units are **MeV/c^2**.

1 MeV/c^2 = (1.60×10^{-19} eV × 1 × 10^{6}) ÷ 9.0×10^{16} m^2 s^{-2} =1.78×10^{-30} kg.

To work out the speed of a particle, we say that **all** its energy is **kinetic energy**.

$$E_k = \frac{1}{2}mv^2$$

Rearranging gives us:

$$v = \sqrt{\frac{2E_k}{m}}$$

In the very high energy interactions that occur in particle physics, energy is turned into mass to produce a large range of different particles. Most of these are highly unstable and last a tiny fraction of a second (about 10^{-15} s to 10^{-18} s). They are often called the **particle zoo**.

2.054 Particles and antiparticles

Each particle has an **antiparticle**. However, antiparticles are not found in normal matter, but arise in:

- high-energy collision experiments,
- interactions with cosmic rays,
- radioactive decay.

We should note the following:

- an antiparticle has the same **mass** as its particle.
- a particle and its antiparticle have **equal** but **opposite charge**.
- a particle and its antiparticle have equal but opposite **spin.** You are not expected to know about it for AS level.
- other **quantum numbers** are the same.
- an unstable particle and its antiparticle have the **same lifetime**.
- some **neutral** particles and their antiparticles are identical (e.g. photon and p° meson).
- other neutral particles and antiparticles are not identical.

For example:

- An electron has a mass of 9.11 × 10^{-31} kg, a charge of -1.6 × 10^{-19} C, and a Lepton number of +1.
- A positron (anti-electron) has a mass of 9.11 × 10^{-31} kg, a charge of +1.6 × 10^{-19} C, and a Lepton number of -1.

The symbol for the electron is e^- and for the **positron** is e^+. A positron is the **antiparticle** to the electron. It carries a charge of +1e, i.e., +1.6 × 10^{-16} C. For other particles, the antiparticle has a bar over the symbol, for example if the proton has the symbol p, the antiproton has the symbol:

$$\bar{\mathrm{p}}$$

This is pronounced "pee-bar".

Note:

In this word processor, placing a bar over a letter gives results that are most unsatisfactory. The line often flies off to a completely different part of the page. If I need to refer to an antiparticle in the text, I will write it like this:

P

i.e. white text on a black background.

2.055 Annihilation

When particles and antiparticles meet, they annihilate each other, releasing their combined mass as energy in the form of **gamma** photons.

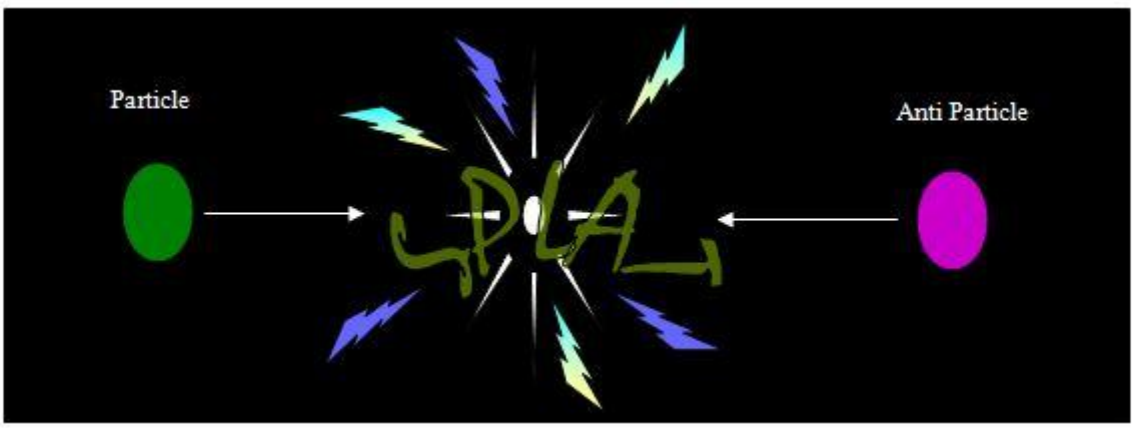


Figure 39 Annihilation of a particle with its antiparticle

Consider the collision between an electron and a positron.

- The gamma photons move off in **opposite** directions; this ensures that momentum is conserved
- Because momentum and energy have to be conserved, two or three photons are created.

$$e^- + e^+ \rightarrow \gamma + \gamma$$

Note that in this case **two** gamma photons are produced. They fly off in opposite directions. A more high energy collision may result in three gamma photons.

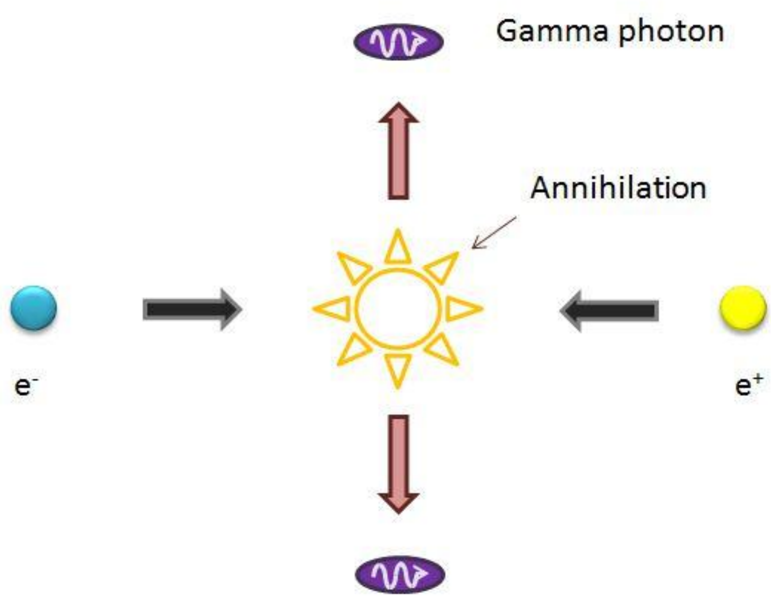


Figure 40 Production of gamma photons by annihilation

If there is **sufficient** energy, other particles may be created as well. For example, the collision between an electron and a positron may give rise to two **muons**:

$$e^- + e^+ \rightarrow \mu^- + \mu^+$$

2.056 Pair Production

The reverse process can apply as well. Electrons and positrons can be formed when a gamma ray passes through matter. A gamma photon can give rise to an electron and a positron, provided the **energy** of the photon is **more than twice the rest mass of an electron**, and that it is **near a nucleus**. This **pair production** is a good illustration of how mass and energy can be changed from one to another.

Two gamma photons meeting will not interact. They just **superpose** and pass through each other. No pair production happens.

A single gamma photon (with energy greater than 1.02 MeV) will form a **positron** and an **electron**, but it has to be **in the presence of a nucleus**. The gamma photon must have the same energy as the rest energies of the electron and the positron added together.

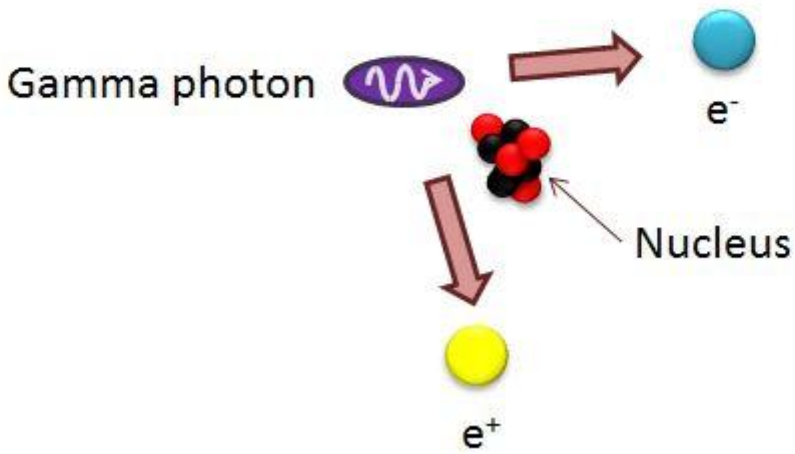


Figure 41 Pair production from a gamma photon in the presence of a nucleus

The photon is pure energy, but it can turn into matter. So, there is a chance that the photon of sufficient energy becoming a positron and an electron. However, they will immediately annihilate back into the gamma photon. So, we wouldn't know that that has happened. To conserve momentum, physicists say that the electron and the positron are in virtual states. Near a nucleus, a **virtual photon** from the nucleus, mediating the **electromagnetic force**, may separate the electron and the positron. The electric field within the nucleus repels the positron and attracts the electron. Therefore, they fly apart and do not annihilate. The positron will annihilate on interaction with another electron, of which there are plenty.

Antiparticles can be made in large quantities in accelerators, resulting from high-energy collisions. They have short lifetimes, about 10^{-10} s because when they meet their equivalent particle, they **annihilate** each other in a burst of energy. It is even possible to make simple **anti-atoms**.

It is thought that there is more matter than antimatter in the Universe. It is possible that antimatter exists in large quantities somewhere, and that there are antimatter stars and planets. None have yet been detected.

Tutorial 2.05 Questions

2.05.1

What is the energy in joules of the following electron energies?

(a) 100 eV

(b) 100 MeV

(c) 10 GeV

2.05.2

What is the speed of an electron at:

(a) 100 eV;
(b) 10 GeV?

2.05.3
(a) The mass of a proton is 1.67×10^{-27} kg. What is this in MeV/c^2?

(b) The rest energy of a Higgs Boson is 126 GeV. What is its mass in kg?

(c) Compare your answer to the mass of a proton (mass = 1.67×10^{-27} kg).

2.05.4

An electron of rest energy 0.511 MeV collides with a positron.
(a) What happens?
(b) 3 identical photons are produced. Calculate their energy in eV and joules.
(c) Calculate the wavelength of the photons.

2.05.5

State and explain the sequence of events in an annihilation.

2.05.6

(a) An electron and a positron each have a rest energy of 0.511 MeV. Show that the minimum energy required for pair production is 1.022 MeV
(b) Calculate the wavelength of a gamma photon of energy 1.022 MeV
(c) Show that a rest energy of 0.511 MeV is equivalent to about 9×10^{-31} kg

Tutorial 2.06 Classification of Particles (Leptons)	
All Syllabi	
Contents	
2.061 Classification	2.062 Leptons
2.063 Quantum Numbers	

2.061 Classification

We can show the way the particles are classified as a tree (*Figure 42*).

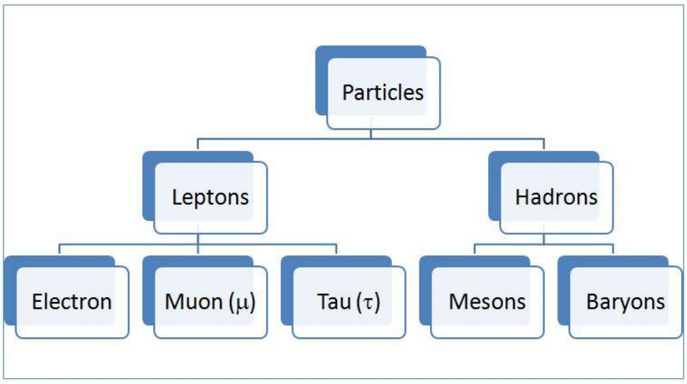


Figure 42 Classification of particles

From this diagram we can see that there are three classes of **leptons** (*Figure 43*)

	Electron	Muon	Tau
Lepton	e^-	μ^-	τ^-
Neutrino	ν_e	ν_μ	ν_τ
Anti-Lepton	e^+	μ^+	τ^+
Antineutrino	$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$

Figure 43 Classification of Leptons

Each lepton has a **neutrino**, an **antiparticle**, and an **anti-neutrino**.

2.062 Leptons

Leptons are **fundamental** particles such as the electron. They are called **leptons** as they are considered to be light weights, although the muon is as massive as a meson and the tau has a greater mass than a gold atom.

Leptons do not feel the strong force. They only feel the **weak** force (e.g. beta minus decay) and the **electromagnetic** force. Neutrinos are neutral, so only feel the weak force. Since they have a mass, they feel gravity, although gravity is too weak to play any role in interactions.

The only stable lepton is the electron. The muon and the tau are highly unstable with very short life times. Each has an escorting neutrino.

Neutrinos are not well understood. While the universe is under a constant hail of neutrinos, they rarely interact with matter, so they are very difficult to measure. During the day you get a hail from the Sun. At night, you are peppered with the little brutes while asleep in your bed. But they won't interact with you (unlike the fleas on the cat…).

There are six particle-antiparticle pairs known. **Leptons** (Greek – "light thing" or "small coins") are the smallest of the fundamental particles. They have the following properties:

- **fundamental** particles without structure
- they interact by the **weak** interaction. If they are **charged**, they interact by the **electromagnetic interaction**, but NOT the strong interaction.

The names of the leptons are:

Lepton	*Symbol*	*Charge*	*Mass*	*Rest Energy*
electron	e-	$-1e$	1/1800 mass of a proton	0.511 MeV
electron neutrino	ν_e	0	Very small	2.2 eV
muon	μ-	$-1e$	2/3 mass of a proton	105 MeV
muon neutrino	ν_μ	0	very small	0.17 MeV
tau	$\tau-$	$-1e$	Mass of gold atom	1800 MeV
tau neutrino	ν_τ	0	Very small	15.5 MeV

Each particle has an **antiparticle**; for the electron, it is the **positron**, the muon the **anti-muon**, and the tau, the **anti-tau**.

Anti Lepton	*Symbol*	*Charge*	*Mass*	*Rest Energy*
positron	e+	$+1e$	1/1800 mass of a proton	0.511 MeV
Electron antineutrino	$\overline{\nu_e}$	0	Very small	2.2 eV
anti-muon	μ+	$+1e$	2/3 mass of a proton	105 MeV
Muon antineutrino	$\overline{\nu_\mu}$	0	very small	0.17 MeV
Anti-tau	τ+	$+1e$	Mass of gold atom	1800 MeV
Tau antineutrino	$\overline{\nu_\tau}$	0	Very small	15.5 MeV

We show the anti-particle either by an opposite charge (e+) or by putting a bar across the symbol ($\overline{\nu_e}$, pronounced "*noo-bar e*"). In text and tables I will represent the antiparticle with white text on a black background, e.g. ν_e.

2.063 Quantum Numbers

There are some quantum numbers that you need to be aware of (*Quantum* is Latin for "how much?".):

- **Lepton** numbers (L). In all interactions the lepton number has to be conserved.
- **Charge** (Q). The charge has to be conserved.
- **Baryon** number (B). In all interactions the baryon number has to be conserved. All leptons have a baryon number of 0 (because they aren't baryons!).
- **Strangeness** (S). This only applies to hadrons. It is not relevant to lepton interactions.

You need to know about **lepton numbers**:

- if it's a lepton, the lepton number is +1;
- if it's an anti-lepton, the lepton number is -1.

The lepton number tells us whether a particle is a lepton or not. If L = 0, it is not a lepton.

There are three smaller categories of lepton number, L_e, L_μ, and L_τ. Each one of these has to be conserved if a lepton interaction is to go ahead. For a muon, L_μ = +1.

Consider this interaction between an electron and a positron:

$$e^- + e^+ \rightarrow \gamma$$

We know that it's an **annihilation**.

Particle	e^-	+	e^+	→	γ	Yes/No
Q	-1	+	+1	→	0	Y
L_e	+1	+	-1	→	0	Y
L_μ	0	+	0	→	0	Y
L_τ	0	+	0	→	0	Y

The gamma photon produced is not a lepton, nor has it any charge. Since neither the electron nor the positron are muons or tau, the muon and tau lepton numbers are 0. If the lepton number and charge are not conserved, the interaction will not proceed.

Why do we have to bother with splitting the lepton number into three separate numbers? Consider this:

$$e^{+} + \mu^{-} \rightarrow \mu^{+} + e^{-}$$

Let's just use charge (*Q*) and lepton number (*L*):

Particle	e^+	+	μ^-	→	μ^+	+	e^-	Yes/No
Q	+1	+	-1	→	+1	+	-1	Y
L	-1	+	+1	→	-1	+	+1	Y

This suggests the interaction should work.

Now let's look at how it works if we split it:

Particle	e^+	+	μ^-	→	μ^+	+	e^-	Yes/No
Q	+1	+	-1	→	+1	+	-1	Y
L_e	-1	+	0	→	0	+	+1	N
L_μ	0	+	+1	→	-1	+	0	N
L_τ	0	+	0	→	0	+	0	Y

We can see from this that the L_e numbers and the L_μ numbers are NOT conserved. This is because the L_e and L_μ numbers (-1 → +1), even though the charge is (0 → 0). So, this interaction does NOT work.

Now consider this:

$$\mu^- \longrightarrow e^- + \nu_\mu + \bar{\nu}_e$$

Particle	μ^-	→	e^-	+	ν_μ	+	ν_e	Yes/No
Q	-1	→	-1	+	0	+	0	Y
L_e	0	→	+1	+	0	+	-1	Y
L_m	+1	→	0	+	+1	+	0	Y
L_t	0	→	0	+	0	+	0	Y

Notice how the **lepton number** and **charge** are conserved for electron, muon, and tau. This tells us that the decay can proceed. If leptons interact with hadrons, the hadrons are considered to have a lepton number of 0.

Tutorial 2.06 Questions

2.06.1

What are the symbol, the charge, and the lepton numbers of the particle anti-tau?

2.06.2

Use quantum numbers to show that this interaction can happen:

$$e^- + e^+ \rightarrow \mu^+ + \mu^-$$

2.06.3

Show that the electron neutrino has a mass of approximately 4.0×10^{-36} kg.

Tutorial 2.07 Classification of Particles (Quarks)	
All Syllabi	
Contents	
2.071 Classification	2.072 Hadrons
2.073 Quarks	2.074 Strangeness

2.071 Classification

We can show the way the particles are classified as a tree (*Figure 44*).

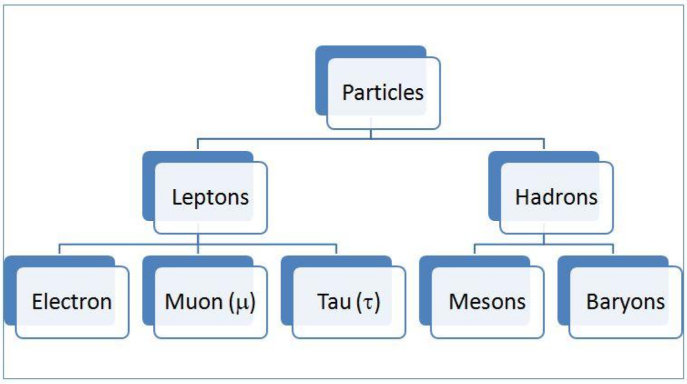


Figure 44 Classification of particles into hadrons

We are going to look at the **hadrons**, which are subdivided into **mesons** and **baryons**.

The key definition of a hadron is that it **feels the strong force**. No other particles feel the strong force.

2.072 Hadrons

- A **hadron** is defined as a particle made of quarks and that feels the strong force.
- A proton is a hadron that feels the electromagnetic force and the strong force.
- A neutron does not feel the electromagnetic force but does feel the strong force.

Electrons feel the electromagnetic force but not the strong force.

2.073 Quarks

Quarks (pronounced "*quork*" as in *pork*) are the fundamental particles from which hadrons are made. **They cannot exist on their own**. Quarks make up the hadrons.

In **baryons** (the "heavy weights") they are found as **triplets**. In mesons (the "middle weights"), they are always in a **quark-antiquark** pair.

There are three main quarks, **up**, **down**, and **strange**. The names have no real significance beyond the imagination of the physicist that dubbed them such. They have corresponding **antiquarks**. There are three others with even odder names, **top** (sometimes called "truth"), **bottom** ("beauty"[!]), and **charm**, which we won't worry about here.

There are three **quantum numbers** associated with quarks:

- **Charge**, expressed as the fraction of the electronic charge. 1/3 $e = 5.33 \times 10^{-20}$ C
- **Baryon** number
- **Strangeness** number, when there are **strange** quarks.
- Each antiquark has equal and opposite values of charge, baryon number and strangeness.

Quark	*Charge (Q)*	*Baryon number (B)*	*Strangeness (S)*
Down (d)	-1/3	1/3	0
Up (u)	+2/3	1/3	0
Strange (s)	-1/3	1/3	-1
Anti-down (d)	+1/3	-1/3	0
Anti-up (u)	-2/3	-1/3	0
Anti-strange (s)	+1/3	-1/3	+1

NOTE:

In many books you will see the anti-particles with a bar over the symbol, for example, ū, ("u-bar") for anti-up. Therefore, I will represent antiparticles by using a white letter on a black background. So, d is to be read as "d-bar", meaning anti-down.

- Baryons are made of three quarks; antibaryons of three antiquarks.
- Mesons are made up of **one quark and one antiquark**.
- Gluons bind quarks together; they are subject to the **strong** interaction.

The strange quark has a quantum number of its own, the **strangeness** number.

The diagram (*Figure 45*) shows the three generations of quarks:

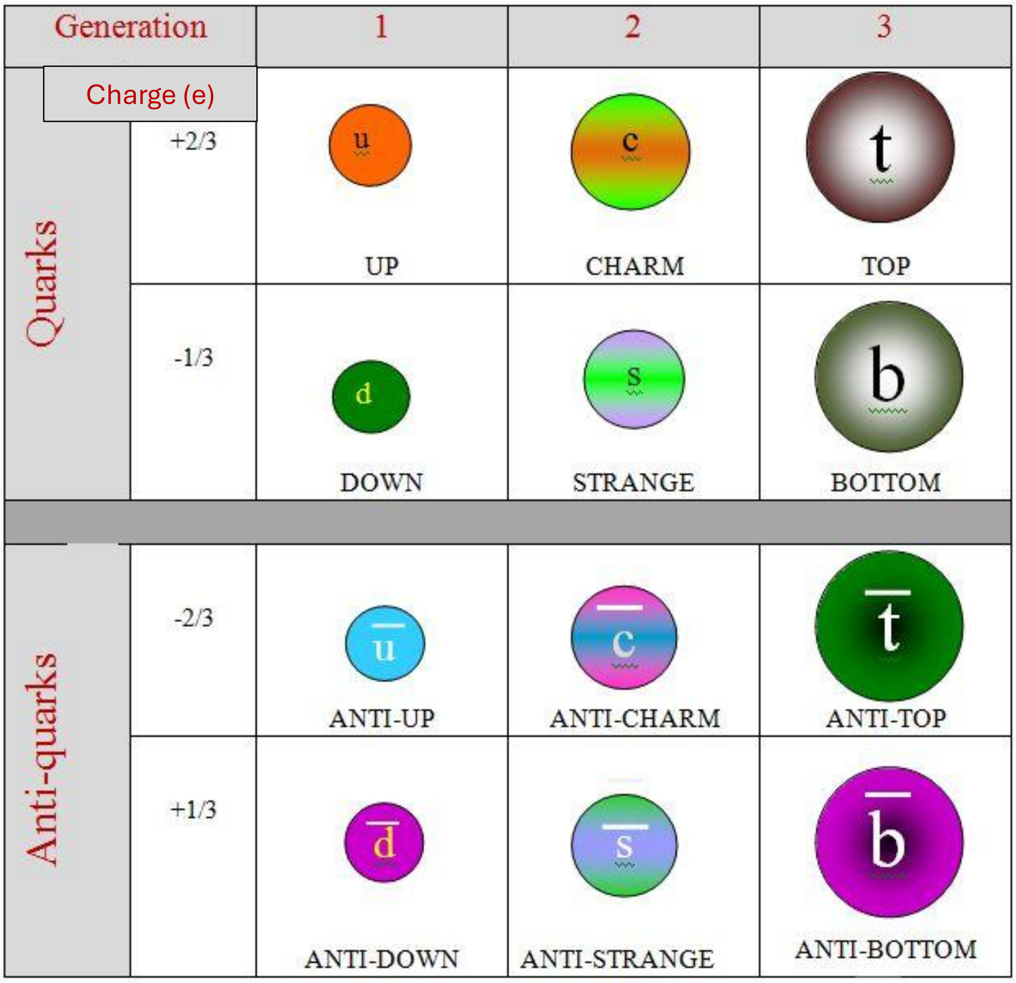


Figure 45 Generations of Quarks

Each quark has a charge. The up, charm, and top have a charge of +2/3 × electronic charge (1.6 × 10^{-16} C). The down, strange, and bottom have a charge of -1/3 × electronic charge (1.6 × 10^{-16} C). The anti-quarks have the opposite.

Physicists see patterns in the quarks. They call this **symmetry**. The **up** quark matches the **down**, the **strange** is balanced by the **charm** (so named because it worked like a charm to support the symmetry). The **top** quark matches the **bottom** quark.

The quark with the lowest mass is the up. The down quark has a slightly higher mass, therefore slightly higher energy. Remember that mass and energy at this level are interchangeable. One of the down quarks in a neutron decays by beta minus decay to an up quark. The hadrons made up from other quarks have a very short lifetimes.

It is wrong to say that the up quark is the most stable, as it implies that quarks can be found singly. Single quarks have never been observed.

2.074 Strangeness

The **strange** quark is an oddity. When the particle zoo was first described in the earliest particle physics experiments, most particles were found to have an average lifetime of about 10^{-23} s (not very long). These particles decayed through the strong interaction.

However, there were some particles whose behaviour was **strange**, in that they lasted about 10^{-10} s (still not that long, but a lifetime compared with the others). The first of these particles was discovered in 1947, but the existence of the **strange quark** was predicted in 1964.

Strange quarks have a quantum number called **strangeness**. For matter, the value of strangeness is strange itself; the strangeness number for the strange quark is **-1**. For the strange anti-quark, it is **+1**. All other quantum numbers for matter are positive, while all other quantum numbers for antimatter are negative.

To work out the **strangeness** of a particle, we use this simple relationship:

Strangeness = (number of strange quarks + number of strange anti-quarks)

For a K+ (anti-strange and up):

Strangeness = 0 + 1 = +1

It is possible to have a strangeness of 2, or even 3 in a very strange baryon.

Pentaquarks

There has been some recent interpretations of results to suggest that groups of 5 quarks are possible. The data are very uncertain, and many physicists are not convinced. The pentaquark forms a group of 4 quarks and 1 antiquark, giving a baryon number of 1.

Tutorial 2.07 Questions

2.07.1

What is the key definition of a hadron?

2.07.2

What is the charge in Coulomb (C) of an up-quark?

Tutorial 2.08 Classification of Particles (Mesons)

All Syllabi

Contents

2.081 Classification

We can show the way the particles are classified as a tree (*Figure 46*).

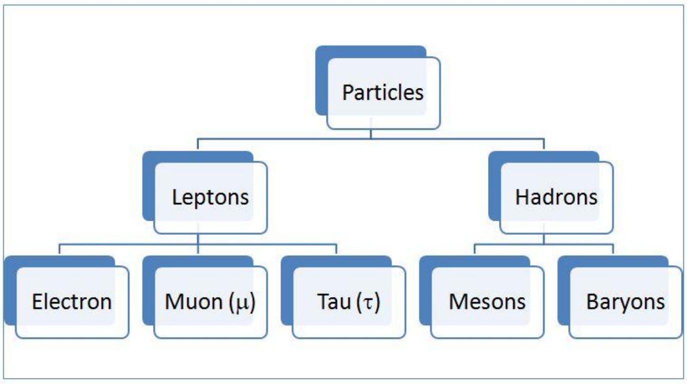


Figure 46 Classification of Hadrons into Mesons

We are going to look at the **hadrons**, which are subdivided into **mesons** and **baryons**.

2.082 Mesons

Mesons consist of **one quark and one anti-quark**. Mesons can feel the strong force, the weak force, and, if charged, the electromagnetic force.

Mesons do not consist of two quarks (or two anti-quarks).

These particles have a smaller rest mass than the baryons (and a lower rest mass than the muon lepton). They have:

- Zero **baryon number**.
- Short lifetimes. The longest lived has a lifetime of 10^{-8} s (not very long).
- Antiparticles

We should note the following:

- Mesons have TWO quantum numbers that must be conserved in interactions. The **charge** is denoted by *Q*, the **baryon number** by *B*. Mesons have a baryon number of 0.
- Mesons have a **lepton number** of 0. This must be conserved in any interactions with leptons.

Here are a few mesons:

Name	***Symbol***	***Q***	***Lifetime (s)***	***Quarks***
Pion	π^0	0	0.8×10^{-16}	Up, anti-up (uu) OR down, anti-down (dd)
	$\pi+$	1	2.6×10^{-8}	Up, anti-down (ud)
Kaon	K+	1	1.2×10^{-8}	Up, anti-strange (us)
	K^0	0	8.9×10^{-11} 5.2×10^{-8}	Down, anti-strange (ds) Strange, anti-down (sd)

2.083 Quantum Numbers

Remember that the meson consists of a **quark and an anti-quark**. Therefore, the charge on a meson is either +1, 0, or -1. It is never anything else like +2/3. If your answer is 2/3, etc, you have forgotten that one quark is an anti-quark.

The baryon number = +1/3 + -1/3 = 0.

Figure 47 below shows the complete menagerie of mesons that contain the **up**, **down**, and **strange** quarks:

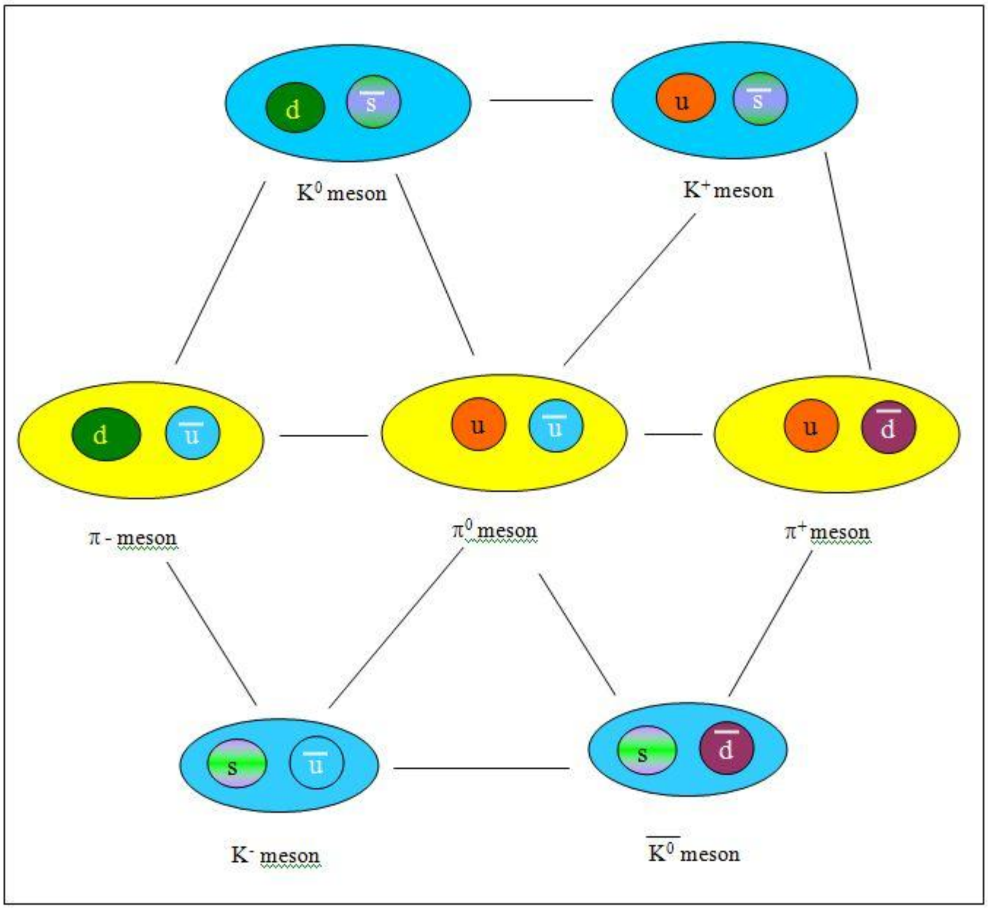


Figure 47 Menagerie of mesons

These are the mesons that can be obtained using the up, down, and strange quarks and their antiparticles. If the quarks are up and down types (quark and anti-quark), a **pi-meson** (**pion**) is formed. There are three pions.

If there is a strange quark, then we get a **Kaon** (K-meson). Kaons always have strange quarks; pions have no strange quarks. There are four **kaons** possible in this diagram.

A considerably bigger particle freak-show can be obtained if the other quarks are involved, but that is not on our syllabus. The weirder mesons are only found in high-energy particle collisions.

The **pion** (π meson) is thought to be involved in transmitting the strong force between baryons. The **gluons** transmit the strong force between the quarks.

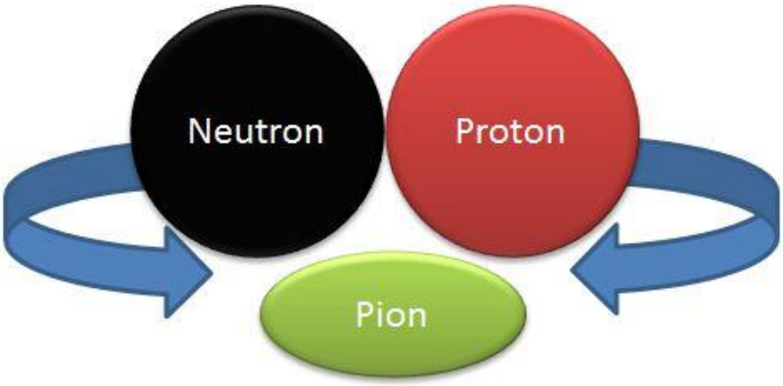


Figure 48 A pion is thought to transfer the strong force

It is thought to shuttle backwards and forwards like a rugby football.

The transmission of the strong force is modelled using "**colour charge**", which is way beyond the syllabus. At university, you will study **quantum chromodynamics**.

2.084 Meson Interactions

Here is a typical meson interaction:

	π_0	→	e^-	+	e^+	+	γ	+	γ	Yes/No
Q	0	→	-1	+	+1	+	0	+	0	Y
B	0	→	0	+	0	+	0	+	0	Y
L_e	0	→	+1	+	-1	+	0	+	0	Y

Note how the quantum numbers *Q*, *B*, and *L* are conserved. The interaction proceeds.

Tutorial 2.08 Questions

2.08.1

What is the quark composition of the π- meson?

2.08.2

Use the baryon number of the quarks to explain why the baryon number of a meson is zero.

2.08.3

Use quantum numbers to show that this interaction can occur.

$$\pi^{+} \rightarrow \mu^{+} + \nu_{e}$$

Tutorial 2.09 Classification of Particles (Baryons)

All Syllabi

Contents

2.091 Baryons

These are the heavyweights of particle physics and include the familiar proton and neutron.

- They are made up of three quarks
- They have quantum numbers such as charge and baryon number, which must be conserved in interactions.
- Baryons have a baryon number of +1. Anti-baryons have a baryon number of -1.
- The lepton number is 0 ('cos they're not leptons!).

Let us look at the properties of the baryons:

Name	*Symbol*	*Q*	*B*	*S*	*Lifetime (s)*	*Anti-particle*
Proton	p	+1	1	0	stable	p
Neutron	n	0	1	0	898	n
Lambda	Λ^0	0	1	0	2.6×10^{-10}	Λ^0
Sigma	$\Sigma+$	+1	1	-1	0.8×10^{-10}	$\Sigma-$
	Σ^0	0	1	-1	7.4×10^{-20}	Σ^0
	$\Sigma-$	-1	1	-1	1.5×10^{-10}	$\Sigma+$
Omega	$\Omega-$	-1	1	-3	0.8×10^{-10}	$\Omega+$

In the exam, you will only be asked about protons, neutrons, and possibly the sigma. So don't spend ages learning these baryons off-by-heart!

Figure 49 shows the quarks for the proton and the neutron:

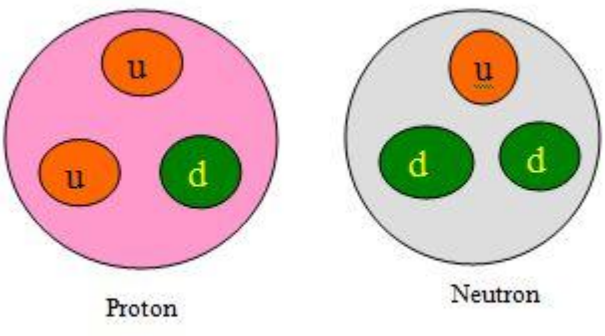


Figure 49 Quarks in a proton and a neutron

In baryons, particles and antiparticles are NEVER found together in the same baryon.

The baryons feel all four of the fundamental interactions.

Gluons hold the quarks together. Two baryons are held together by the exchange of **pions**.

The **proton** is the only baryon that is stable in isolation.

The **neutron** on its own decays to a proton by beta minus decay after about 12 minutes. The decay is as a result of the **weak interaction** that occurs within nucleons.

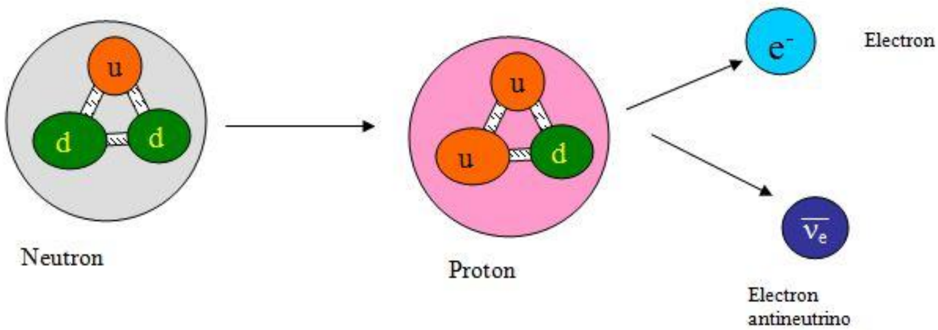


Figure 50 Decay of a neutron by beta minus decay

Some very short-lived baryons can have a charge of +2.

2.092 Anti-baryons

The **anti-proton** and **anti-neutron** are shown in *Figure 51*:

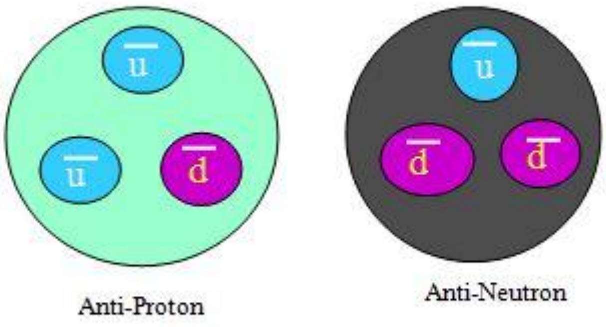


Figure 51 Anti-baryons

There are other anti-baryons, for example, the **anti-sigma minus**, Σ-, which is the **antiparticle** to the **sigma plus** (Σ+). It does NOT have the same quark composition as the sigma minus.

It is possible to make simple anti-atoms, like **anti-hydrogen**:

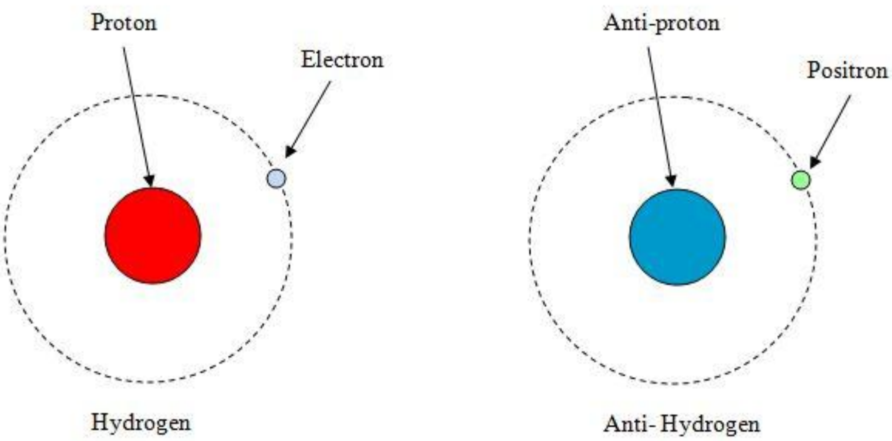


Figure 52 Simple anti-atom

Anti-hydrogen, H ("H-bar") has been made at CERN, but the atoms annihilate as soon as they touch matter. Powerful magnetic fields are needed to keep the little brutes in place. Recently (June 2011) 300 anti-hydrogen atoms were reported to have been made, some lasting about 1000 s (17 minutes). In a perfect vacuum, there is no reason why the anti-atoms shouldn't last for ever. When CERN is fully operational, they reckon to be able to make 10^7 hydrogen anti-atoms every second. At that rate, they will make 1 mole (6×10^{23} atoms) in about 100 000 million years. That's a long time.

Figure 53 A representation of the anti-author (I'm older and even uglier now!)

There may be parts of the universe where there is complex antimatter material, but there is certainly no evidence for it.

2.093 Strange baryons

Strange baryons have one or more **strange** quarks. The strange baryons still have a baryon number of 1, and must have a charge of -1, 0, +1. Strange anti-baryons will have the opposite charge of +1, 0, -1. The strangeness number can be -1 (1 strange quark), or -2 (2 strange quarks), or -3 (3 strange quarks).

Here are some points about the strange quarks:

- Unlike down and up quarks, strange quarks are made in pairs.
- This is a pair-production process caused by collisions in the quark-gluon plasma.
- This is a gaseous material that occurs in extreme conditions, such as those experienced 10^{-40} s after the Big Bang.
- The conditions can be created in powerful particle accelerators.
- The strange quark experiences all the fundamental forces.
- Particles that have a strange quark have a rather longer lifespan than expected (about 10^{-10} s rather than 10^{-15} s).

Figure 54 shows baryons containing one strange quark:

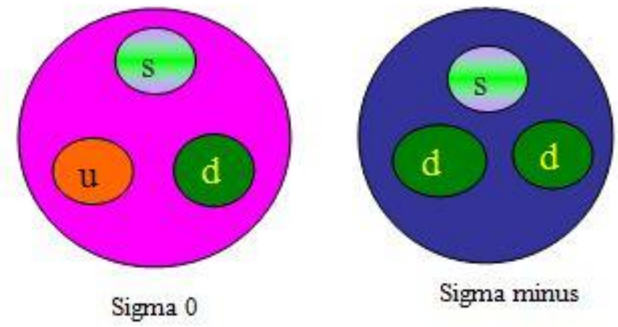


Figure 54 These baryons contain one strange quark

The Xi-baryon (Ξ) has two strange quarks. The strange symbol is "Xi", a Greek upper-case letter 'X'. The Ξ^- baryon has a quark composition of *dss*, while the Ξ_0 baryon is *uss*. The Ω- ("omega-minus") baryon has 3 strange quarks, *sss*.

If the strangeness number is conserved during interactions involving strange baryon, the interaction is mediated by the **strong force**.

If the strangeness is NOT conserved during the interaction, the interaction proceeds (provided that other quantum numbers are conserved) but it's through the **weak interaction**.

There is a whole zoo of different particles that contain other types of quark.

Tutorial 2.09 Questions

2.09.1

This question is about the neutron.

(a) What is the quark combination of a neutron?

(b) Show that the charge is 0.

(c) Explain how the neutron has a baryon number of 1.

(d) An isolated neutron lasts about 12 minutes. What does it decay to?

2.09.2

State two ways that an anti-neutron is similar to a neutron.

How is it different to a neutron?

An anti-neutron will decay. What will it decay to?

2.09.3

The sigma baryons have a strangeness number of -1.

(a) How many strange quarks do they have?

(b) What is the quark composition of the sigma plus (Σ^+) baryon?

(c) What is the quark composition of the sigma minus anti-baryon (Σ-).

(d) How does the Σ- differ from the Σ-?

Tutorial 2.10 Particle Interactions

All Syllabi

Contents

2.101 Conservation rules in Interactions

All particle interactions must follow certain **conservation rules** in order to happen. These are:

- Energy must be conserved (as in all physics interactions);
- Momentum is conserved.
- Charge is conserved.
- Lepton number is conserved.
- Baryon number is conserved.

If there are **strange particles** involved and **strangeness** is conserved, the **strong** interaction is responsible. If strangeness is not conserved, the **weak** interaction mediates the particle interaction.

Figure 55 shows the annihilation process between a proton and an antiproton.

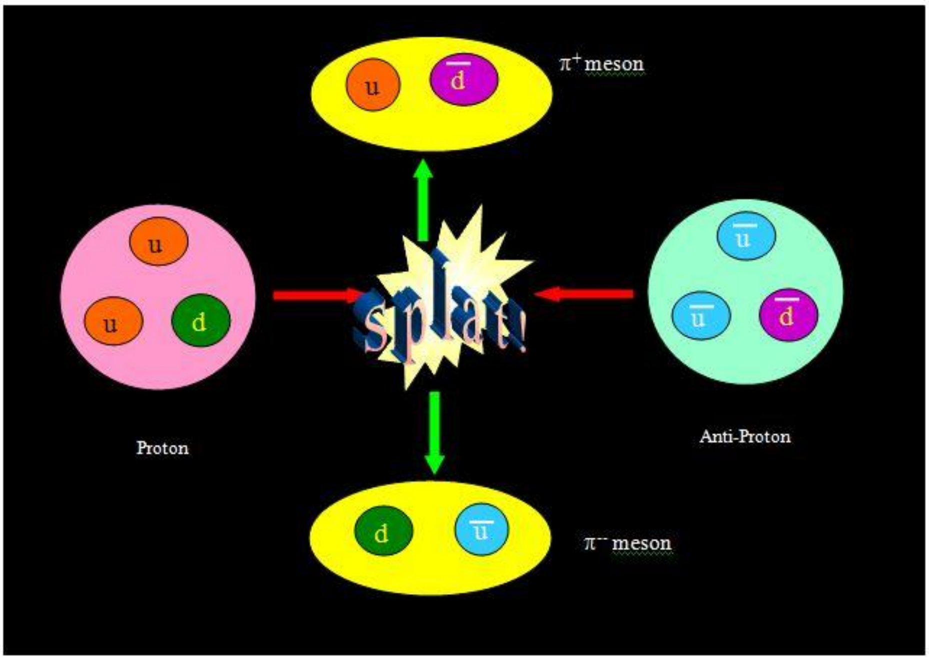


Figure 55 Annihilation of a proton and anti-proton to make positive and negative pions

In this case, one anti-up and one up quark annihilate to produce a burst of energy. There are an up and anti-up, and a down and an anti-down left over. (The black cells indicate antiparticles.) The energy will be lost as **photons**.

Quarks	u d u	+	udu	→	ud	+	ud
Charge	+1	+	-1	→	+1	+	-1
Baryon Number	+1	+	-1	→	0	+	0
Lepton Number	0	+	0	→	0	+	0

2.102 Particle Decay

Let us look at Kaon decay, using the K+ meson. Kaons are strange particles because they have a quark (or anti-quark) that belongs to the strange family.

$$K^{+} \rightarrow p^{+} + \pi^{0}$$

Analyse the quantum numbers:

Q:	+1	→	+1	+	0
B:	0	→	0	+	0
L:	0	→	0	+	0
S:	+1	→	0	+	0

The strangeness number of **+1** is because it’s an **anti-strange** quark. Notice that the **strangeness** is NOT conserved. This decay will go ahead but will do so by the **weak interaction**. For the strong interaction to be involved the strangeness must be conserved.

Baryons decay in the same way, following the same rules. Here are some typical decays:

n	→	p	+	e- +	$\overline{\nu}_{\varepsilon}$ (β- decay)				
Λ^0	→	p	+	$\pi-$	or	n	+	π^0
$\Sigma+$	→	p	+	π^0	or	n	+	$\pi+$
Σ^0	→	Λ^0	+	γ				
Σ	→	n	+	$\pi-$				
Ω	→	Λ^0	+	K-				

Most baryons in the particle zoo have strange looking symbols. They are Greek capital letters. Λ = lambda, the letter 'L'; Σ = sigma, the letter 'S'; Ω = omega, the letter long O, 'Ō'.

Mesons have lower case Greek letters: π = pi, a Greek letter 'p'.

The proton is the only stable baryon. All the others spontaneously decay, although the neutron within a nucleus is stable, apart from beta decay.

- Baryons decay to **protons**, either directly ($\Sigma+ \rightarrow p^+ + \pi^0$) or indirectly ($\Omega- \rightarrow \Lambda^0 + K$, then $\Lambda^0 \rightarrow p^+ + \pi-$).
- Mesons decay to **photons** or **leptons**.

As in radioactivity, the decay of particles is **random**. The values shown on data sheets are the **mean lifetimes**, not half-lives.

2.103 Feynman Diagrams

Particle interactions can be quite complex to describe, but they have been represented in quite a simple way by **Feynman diagrams**. These were devised by Richard Phillips Feynman (1911 - 1988), an American Physicist. He introduced them to a conference in 1941 (Physics carried on as usual despite the War) attended by the world's leading physicists. Neils Bohr (whose model of the atom we still use at this level) was outraged, and only just restrained himself from thumping Feynman.

Feynman diagrams have evolved from the simple doodles that they were then, but at this level, we will use them as little more than a doodle.

Let us look at a beta minus decay (*Figure 56*):

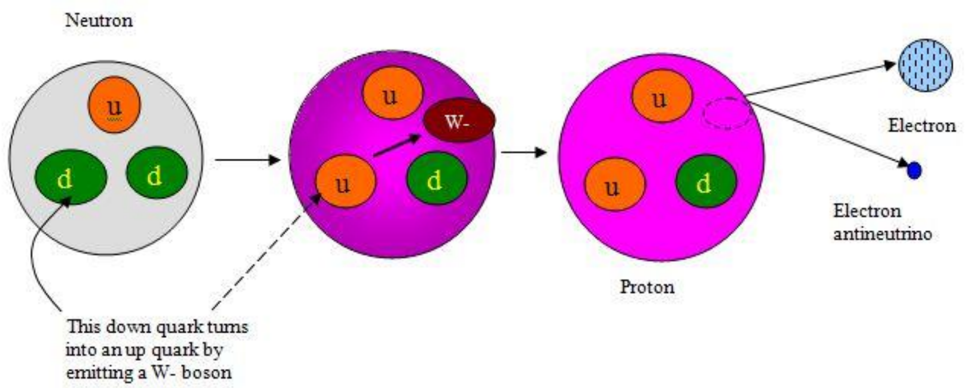


Figure 56 Beta minus decay at the nucleon level

The Feynman diagram is a **space against time diagram**. We are interested in the before, during, and after:

- Before - we have the neutron.

- During - the down quark emits a W- boson.
- After - the boson turns into the electron and electron antineutrino.

The Feynman diagram looks like this (*Figure 57*):

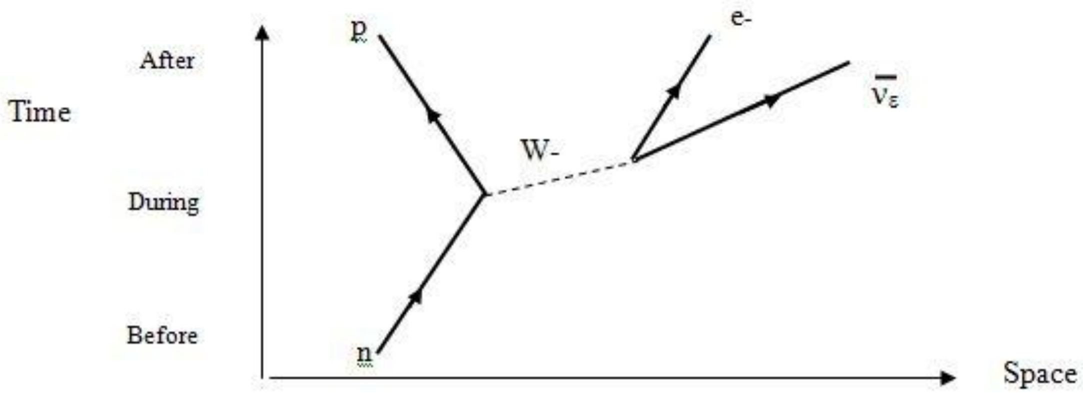


Figure 57 Feynman diagram of a beta minus decay

Often, we miss out the space and time axes. This is shown in *Figure 58* which also shows what happens to the quarks'

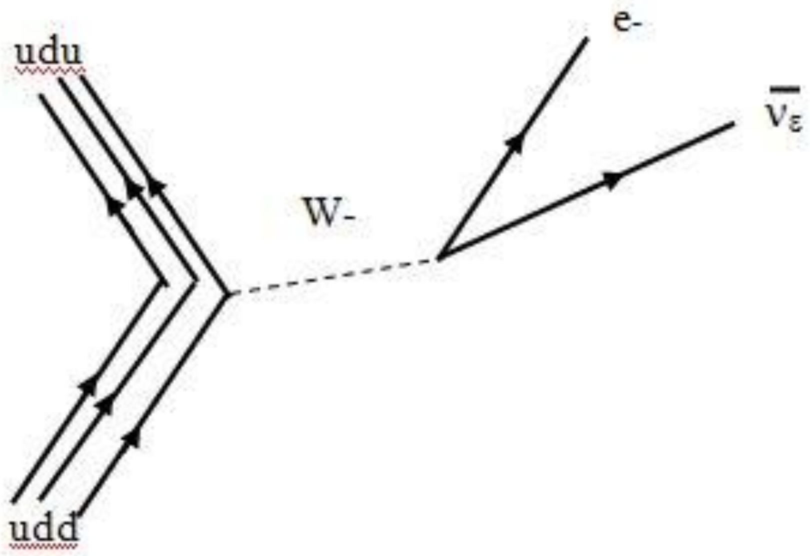
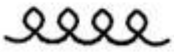


Figure 58 Feynman diagram at the quark level showing a beta minus decay

A diagram like this will get you the marks in the exam.

However, there are some further rules as suggested by the Institute of Physics:

- A Feynman diagram represents before, during, and after.
- The **interaction** is shown by a line going **upwards** at a diagonal. You can only go forwards in time.
- A wiggly line represents an interaction made by a **photon**. 
- A straight dotted line represents a **W- or W+ boson**. You don't need to know about a Z. --------
- A "curly-wurly" line represents a **gluon**. 
- The arrow from a particle is away from the interaction; the arrow for the antiparticle points towards the interaction.

So, the Feynman diagram for out beta decay becomes:

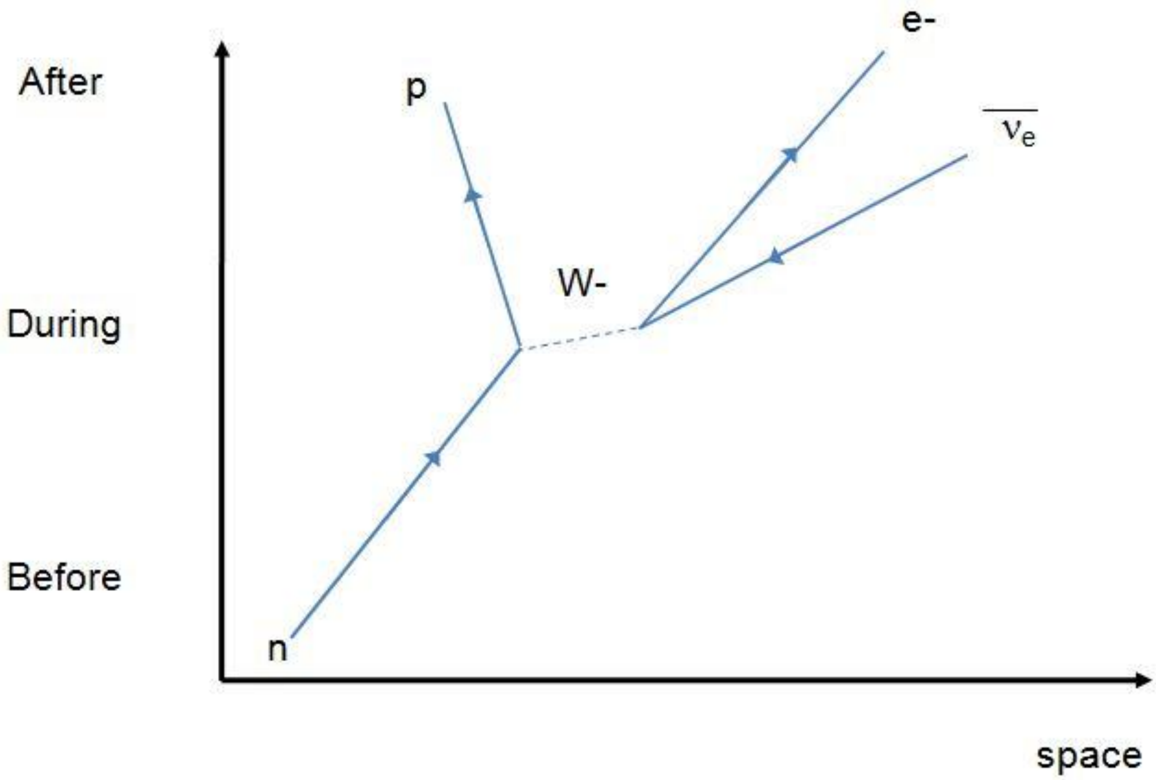


Figure 59 Feynman Diagram to show beta minus decay showing IOP symbols

The picture here suggests that the electron antineutrino is coming in to participate in the interaction. It is the result of the interaction, but, because it's an antiparticle, the arrow points downwards. If this is confusing, just change the direction of the arrow. You won't lose any marks.

There are variations on beta decay that we will sum up, using Feynman diagrams.

2.104 Beta Plus decay

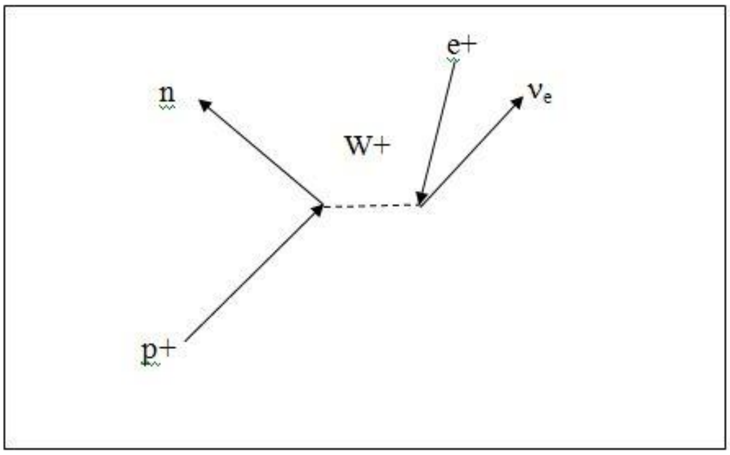


Figure 60 Feynman diagram of beta plus decay

In **beta plus decay**, a proton turns into a neutron. The positive charge is transferred by the W+ boson, which then becomes a positron and an electron neutrino. Note how the positron arrow points towards the interaction, as the positron is an antiparticle. Beta decay occurs in proton rich nuclei.

Here is an example:

electron neutrino

$$^{11}_{6}C \rightarrow ^{11}_{5}B + e^{+} + \nu_{\varepsilon}$$

positron

Figure 61 A typical beta plus decay

Beta plus decay is not an anti-particle version of beta minus decay. The proton is not an anti-neutron for a start!

2.105 Electron Capture

Electron capture is another way in which a proton can be turned into a neutron:

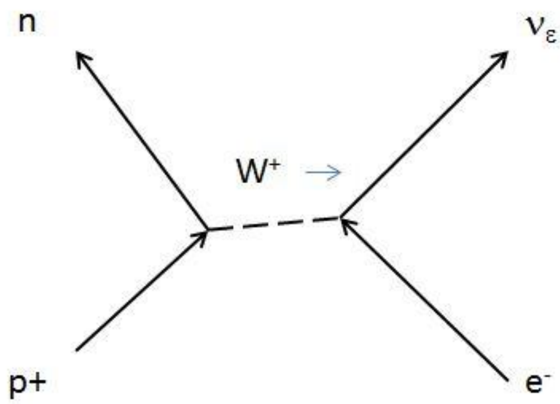


Figure 62 Feynman diagram showing electron capture

The electron falls from one of inner shells. It is attracted by the electromagnetic interaction, but the negative charge is transferred to the proton by the **W^+ boson**. An electron neutrino is emitted.

Here is an example:

$$^{59}_{28}\mathrm{Ni} + \mathrm{e}^- \rightarrow {}^{59}_{27}\mathrm{Co} + \nu_e$$

Figure 63 Typical electron capture event

Note how the nucleon number stays the same, but the proton number decreases by 1.

2.106 Electron Collision

Electron collision is slightly different. The electron strikes the nucleus from outside:

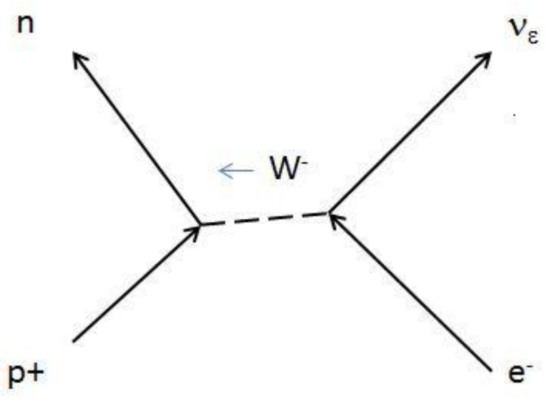


Figure 64 Feynman diagram of an electron collision

In this case the negative charge is transferred from the electron to the proton using the W^- boson. To ensure that all quantum numbers are balanced, an electron neutrino is emitted.

2.107 Neutrino Capture

Neutrino capture is the way that physicists can detect neutrinos. Interactions between neutrinos and nuclei are very rare, despite the fact that the Universe is alive with the little brutes.

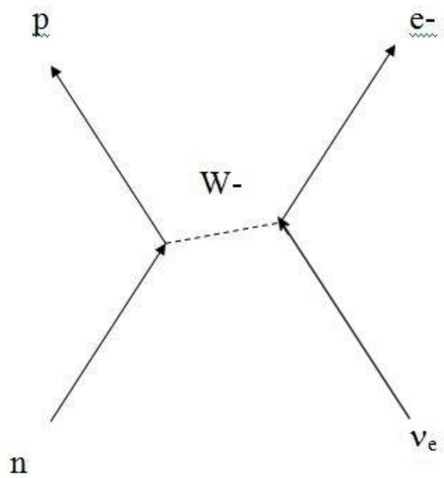


Figure 65 Feynman diagram of a neutron capture event

The capture of an **electron neutrino** leads a neutron to be converted to a proton, with the emission of an electron. The electron ionises another atom. This causes photon emission which can be detected using a **photo-multiplier tube**, which picks up the tiny flash and sends it to a computer.

The Feynman diagram shows the **capture of an electron anti-neutrino**.

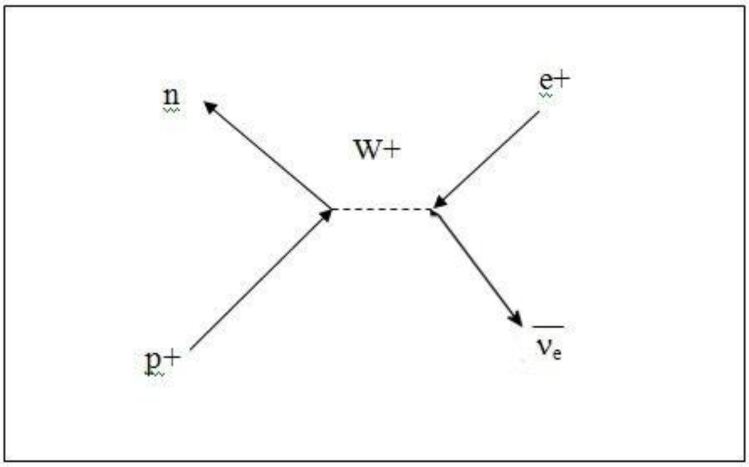


Figure 66 Feynman diagram of an electron anti-neutrino capture event

In this case, a positron is emitted, the charge being transferred by the W+ boson.

2.108 Proton-Proton Collisions

Powerful accelerators like that at CERN can make protons collide with each other at very high speed. We know that protons consist of up up and down quarks. There are also gluons that are holding the quarks together. Added to that there are virtual quarks and antiquarks. Nucleons are very dynamic systems, which are not easy to keep up with.

When the two protons collide, there is more energy released than would be expected from the equation $E = mc^2$. This is because there is extra energy due to relativistic effects as the protons reach the speed of light. As long as **momentum** and **energy** are conserved, this energy is turned into matter in a variety of forms:

- Z bosons - these have a life time of 3×10^{-25} s, and they decay to an electron-positron pair, or a muon-antimuon pair.
- Higgs bosons which have an even shorter lifetime.
- W bosons - these have a charge that is positive or negative, therefore they cannot decay by particle-antiparticle pairs.

- Top quarks.
- A jet of all sorts of different particles.

The results of these experiments require powerful detectors and computers, as well as very bright people, to interpret them.

Here is a Feynman diagram of a proton-proton collision that leads to W+ and W- bosons:

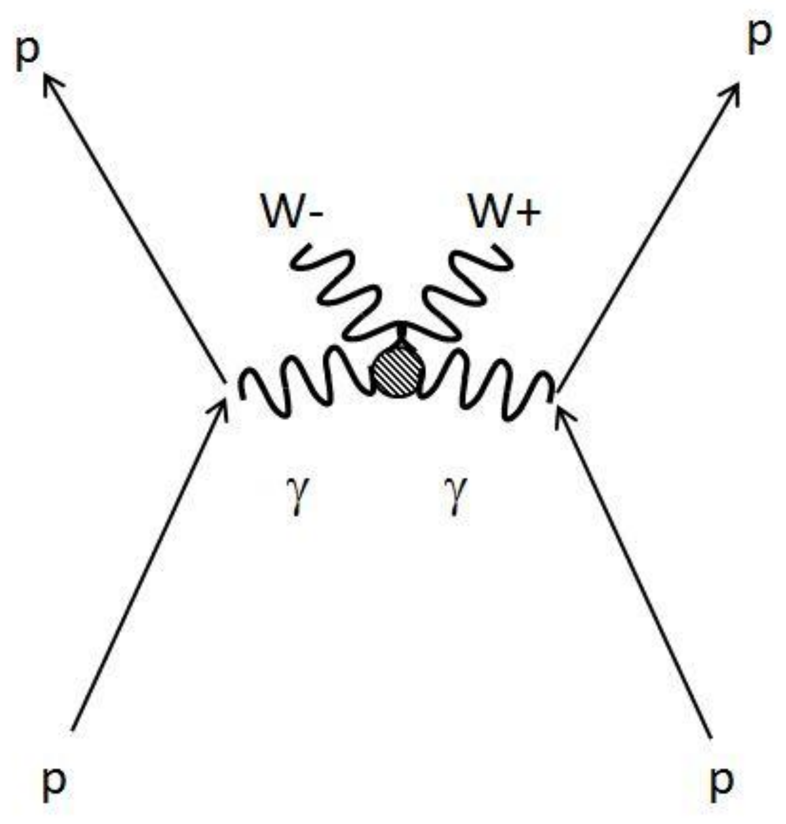


Figure 67 Feynman diagram of a proton-proton collision giving rise to W+ and W- bosons and virtual photons

When the two protons collide, the energy of the collisions initially is given off as a two virtual photons which form a very short-lived particle that then is converted to a W+ and W- boson.

The W+ boson can then decay by the **weak interaction** into an **antilepton** and a **neutrino**:

$$W^+ \rightarrow e^+ + \nu_e$$

$$W^+ \rightarrow \mu^+ + \nu_\mu$$

$$W^+ \rightarrow \tau^+ + \nu_\tau$$

Figure 68 W+ boson decay to anti-leptons and neutrinos

The W- boson can decay by the weak interaction to a **lepton** and an **antineutrino**:

$$W^+ \rightarrow e^+ + \nu_e$$

$$W^+ \rightarrow \mu^+ + \nu_\mu$$

$$W^+ \rightarrow \tau^+ + \nu_\tau$$

Figure 69 W- boson decay to leptons and antineutrinos

Tutorial 2.10 Questions

2.10.1

Write down the 5 quantities that must be conserved for a particle interaction to occur.

2.10.2

Show that this interaction can proceed:

$$p^+ \rightarrow \mu^+ + \nu_\mu$$

2.10.3

Show that this decay is possible for the lambda baryon.

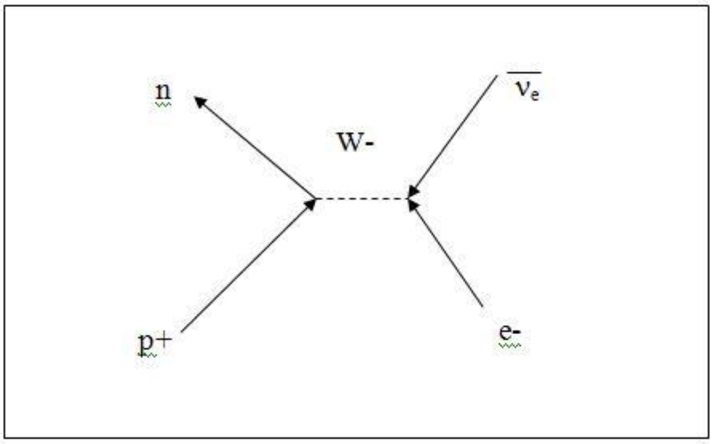
$$\Lambda^0 \rightarrow p^+ + \pi^-$$

2.10.4

Use the conservation of quantum number to explain why, in beta minus decay, an electron antineutrino is observed instead of an electron neutrino.

2.10.5

This image appeared on my old website for a number of years. (Tut-tut) Why is it wrong?



2.10.6

Draw a Feynman diagram to show the interaction between two electrons, showing the exchange particle.

Tutorial 2.11 Exchange Particles	
All Syllabi	
Contents	
2.111 Particles and Interactions	2.112 Virtual Particles
2.113 Graviton	2.114 Photons
2.115 Gluons	2.116 Weak Interaction

2.111 Particles and Interactions

All interactions are mediated by **exchange particles**. That means that interactions don't just happen, but a particle of some kind is involved. The particles will transfer force, and charge where charged particles are involved.

The larger the exchange particle, the shorter the range of the force. Since gravitons and photons have no mass, their range is **infinite**.

Exchange particles are referred to as **gauge bosons**. They were first identified by Satyendra Nath Bose (1894 - 1974), an Indian mathematician and theoretical physicist. The gauge bosons are:

- elementary particles.
- exchanged between interacting particles.
- virtual.

2.112 Virtual Particles

Virtual particles exist for a limited time in time and space. That means that energy and matter are borrowed for a short time to transfer the force. Then they are paid back to the matter (without interest). However, the particle from which the matter was borrowed might not get it back. An example of this would be the W- boson that owes its brief existence to the down quark from which it has borrowed energy and mass. Enough energy is given to the quark to make it an up-quark. The rest of the energy and mass are returned to matter in the form of an electron and an electron antineutrino. The "ripped off" down quark is now an up quark. See *Figure 70*.

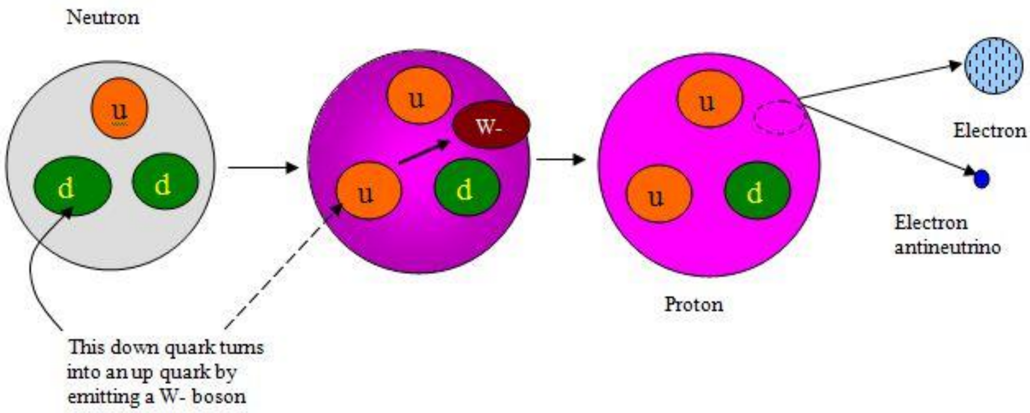


Figure 70 The W- boson borrows energy and transfers it back to matter.

This kind of borrowing and payment back is going on all the time between nucleons.

We can model this as a bank. Banks lend money to other organisations. Most of the time they get the money back (with interest). Occasionally an organisation defaults and does not pay the money back. The money has not disappeared; it has gone into the accounts of the organisation and from there into other organisations (and the directors?). Recently we have seen banks producing ever more strange "products" (scams) which we as taxpayers have had to pay for, while a few very rich individuals and organisations have pocketed it all. Some parallels between the sub-atomic world and the world of high finance?

One thing is for sure. Physicists and bankers both don't fully understand their respective worlds. However, physicists will say, "We're not sure what is going on here. We don't think our data are correct." Bankers will say, "We have some wonderful packages of derivatives, which you can buy and use for leverage."

2.113 Graviton

This boson has not been found but is thought to be mass-less. Since there are so many big objects pulling on each other due to **gravity**, presumably the Universe is crawling with the little brutes.

Gravity is a very weak force. It is so small that it is ignored in particle interactions. It is a significant force between stars and planets, both of which have huge masses. It is only attractive; it is never repulsive. Gravity is the force that shapes the Universe over thousands of millions of years.

Feynman diagrams are irrelevant in gravity.

2.114 Photons

The forces between electrically charged particles are thought to be transmitted by photons, which are emitted and absorbed by the particles. We normally associate photons with the particle properties of electromagnetic waves. Since the photons are involved transmitting the force, they have never been seen. If one were captured, it would have been taken "off task". This is why you don't get flashes of light when you pull or push something. So, we describe them as ghost photons or **virtual photons**. Photons mediate both pulls and pushes. The quantum mechanism is very complex.

In a Feynman diagram, photons are represented by a wavy line:

The Feynman diagram shows an interaction mediated by a photon:

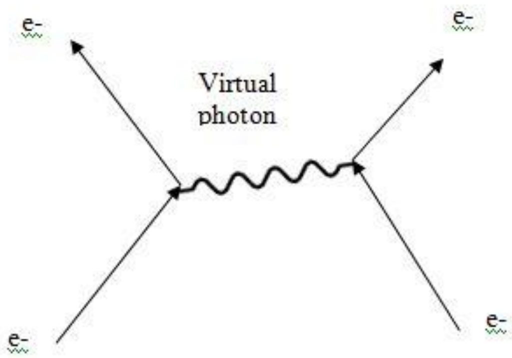


Figure 71 Feynman diagram of electromagnetic interaction mediated by a virtual photon.

2.115 Gluons

Remember that the nucleus is very **tiny** compared to the size of an atom; its diameter is about 10^{-14} m as opposed to 10^{-10} m for an atom. If the atom were the size of the school canteen, the nucleus would be the the size of a pea (or sweet-corn) dropped in the middle.

In this tiny space there are lots of protons, all positively charged. Why does the nucleus not fly apart? The answer is provided by the **strong nuclear force** which holds the nucleons together. Its **attractive force** balances the **repulsive** forces of the protons.

At very short ranges, below 0.5 **femtometres** (0.5×10^{-15} m) the strong nuclear force is **repulsive**. It is **attractive** up to its maximum range of 3 fm (3×10^{-15} m). If we plot a graph of force against distance, we will see (*Figure 72*).

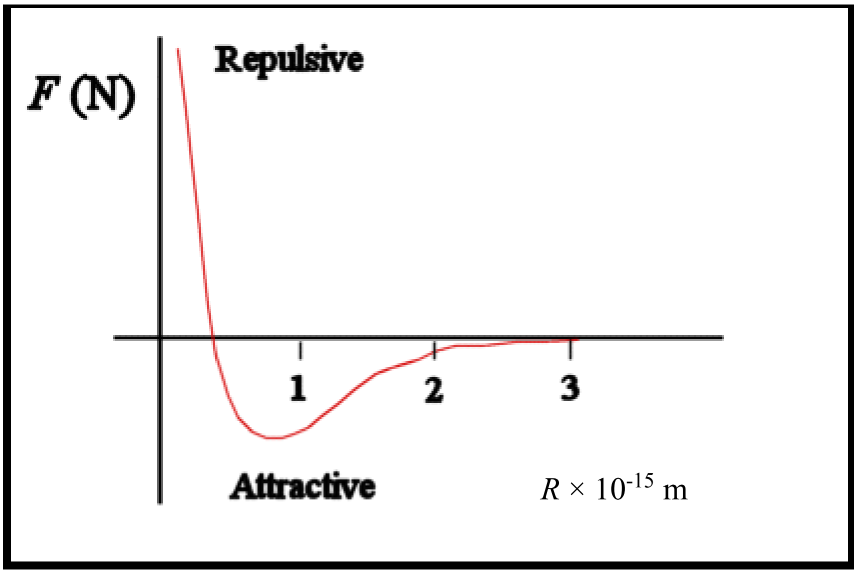
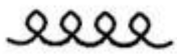


Figure 72 Force distance graph for the strong force

The repulsive force between the two protons is in the order of **200 N** (yes, 200 N). So, it is a very strong force.

The strong force is mediated by **gluons**. In Feynman diagrams, they are shown as a spiral line:



Gluons were first proposed by the American Physicist Murray Gell-Mann (1929 - 2019) in 1962. Gluons have a rest energy between 0 (in theory) and 20 MeV (experimental limit), making them up to 40 times as massive as an electron. Their range is about 3 femtometres (3×10^{-15} m).

As separate particles, **gluons** have never been directly identified. They are however the mediators of the **strong nuclear force** and there is compelling indirect evidence for them. They are thought to be fundamental particles. There are eight gluons that have been identified theoretically from **quantum chromodynamics**, each having a different "colour", although all have zero rest mass and zero charge. Gluons act on quarks, changing the colour charge of each quark. The mechanism is complex, and way beyond what we need to know here.

We can represent the action of gluons as **bonds** between quarks (*Figure 73*).

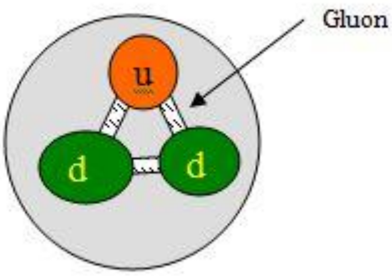


Figure 73 Simplistic diagram to show how gluons act between quarks.

The simple Feynman diagram (*Figure 74*) represents the action of a meson binding a proton and a neutron. Remember that gluons act between quarks. It is thought that mesons are the vehicles that carry the gluons for the strong force between nucleons.

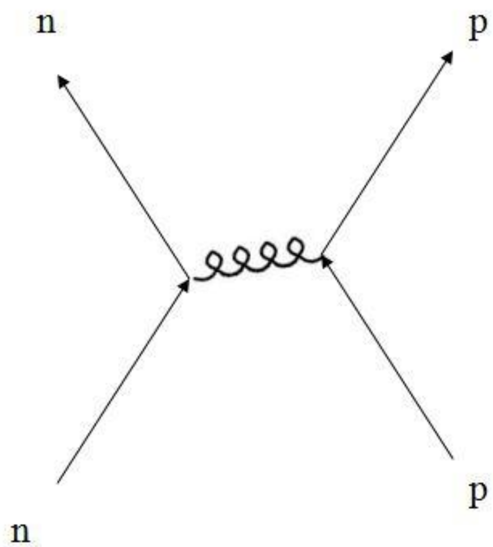


Figure 74 Feynman diagram showing a meson bind a neutron and a proton.

Some theoretical physicists have suggested that swarms of gluons can exist in **glue-balls**. This is possible because of the colour charge and the strong force. Identification of glue-balls has proved extremely difficult.

2.116 Weak force

These are thought to mediate the **weak force**. **W+** mediates beta plus decay, **W-** beta minus. Both have a mass of 80 GeV/c^2. The weak force is not well understood. Since the bosons are very massive, the force is very short range, about 10^{-18} m.

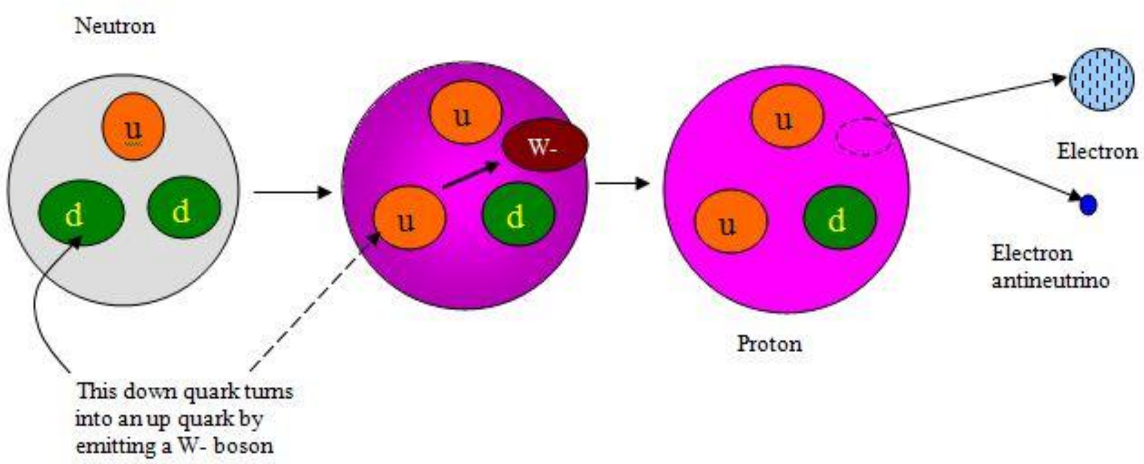


Figure 75 How a down quark changes to an up quark by emission of a W- boson

The **W- boson** is formed from a neutron as it decays into a proton and an electron antineutrino.

In beta minus decay down quark gains enough energy (and mass) to form a W- boson, which then turns into an up quark, and the remaining mass being ejected as an electron and an electron anti-neutrino. The W- boson transfers the force and the charge. Therefore, the electron gains a negative charge of -1e, and the force accelerates both the electron and the anti-neutrino. The electron travels at about 1/3 the speed of light (i.e. 1×10^8 m s^{-1}). The anti-neutrino travels even faster. Momentum is conserved.

However, it is also possible for an electron antineutrino to interact with a neutron. The W- boson mediates the interaction and is turned into an **electron**. The neutron turns into a proton. The interaction is shown here:

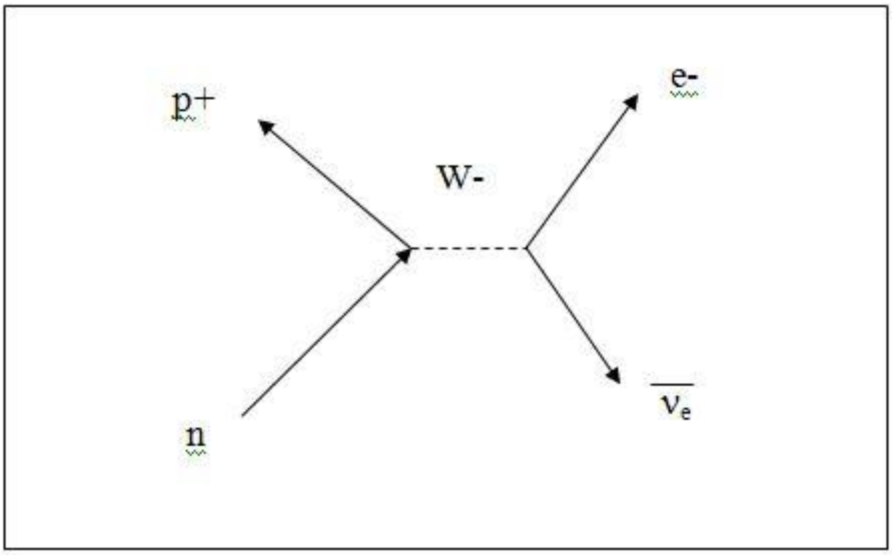


Figure 76 Feynman diagram showing role of the W- boson in beta- decay.

The **Z boson** is so called because it has zero charge. It has a mass of 90 GeV/c^2. The role of the **Z** boson is complex.

The masses of the W and Z boson are 4 times the mass of a gluon.

In **nuclear fusion** in stars nuclei are squashed together really hard. The repulsive electromagnetic force is overcome, so that the nuclei are close enough together for the strong force to bind them.

In the first picture (*Figure 77*), two hydrogen nuclei (protons) are close, but are repelling.

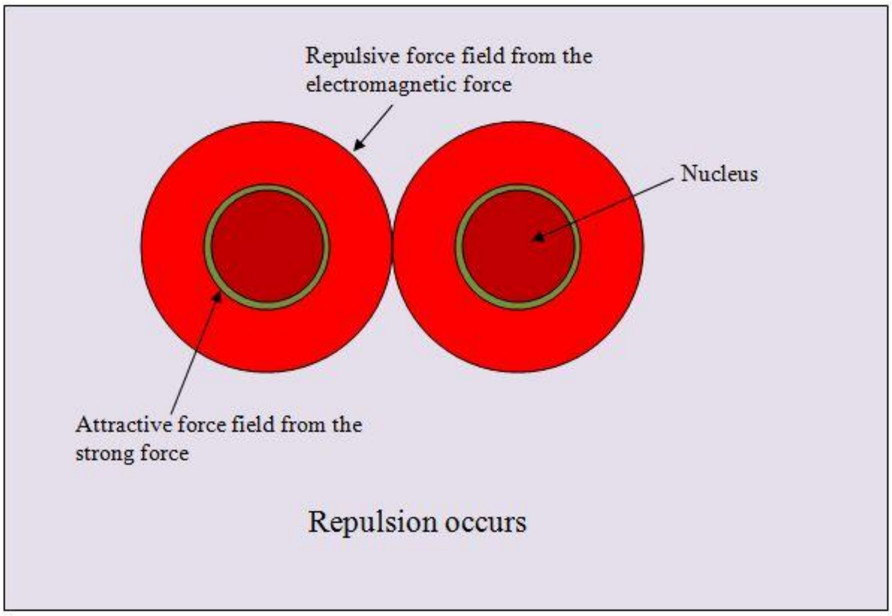


Figure 77 Two hydrogen nuclei brought up close to each other will repel.

Squash them even harder, and they go together, so that the strong force binds them (*Figure 78*).

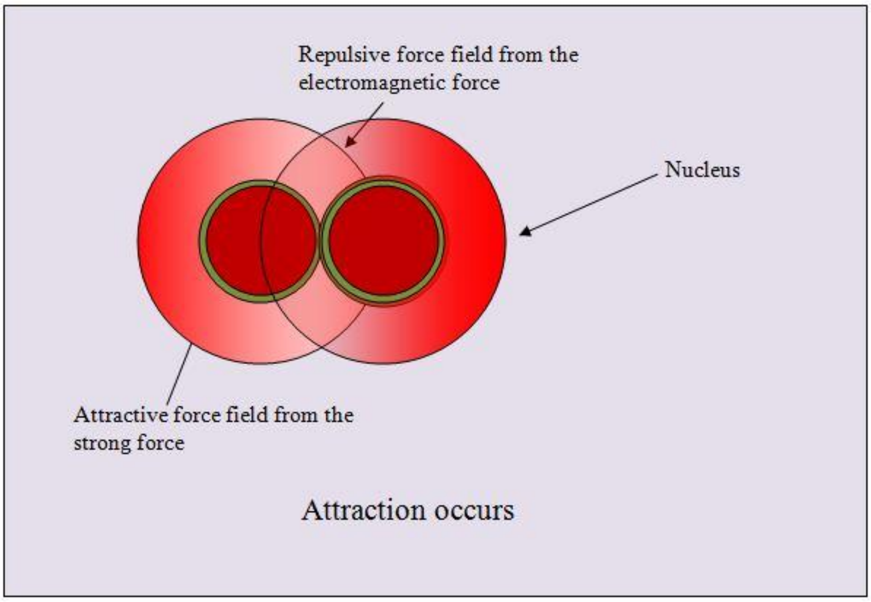


Figure 78 The attraction of the strong force overcomes the repulsion of the electromagnetic force

So, we have two protons bound together. This will lead to beta plus decay, where the one of the protons turns into a neutron, emitting a positron and an electron neutrino. The charge and force is transferred by the W+ boson (*Figure 79*).

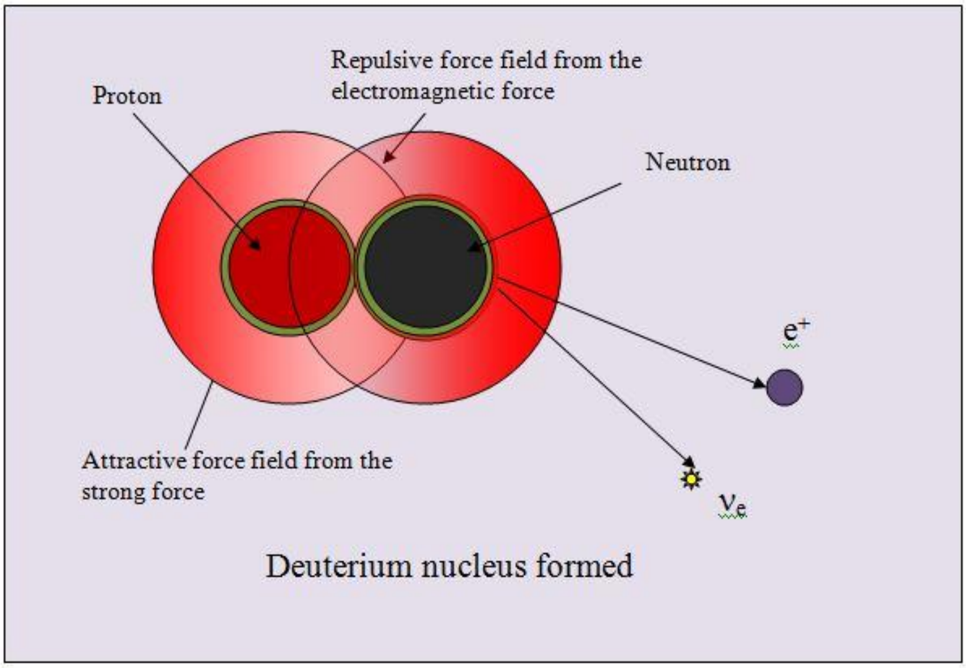


Figure 79 Neutron formed from a proton by the transfer of the W+ boson.

Thus, we have a **deuterium** nucleus formed. Further fusion reactions occur to form helium (and then other materials) in stars. You will see more of this in A2.

Tutorial 2.11 Questions

2.11.1

How can a particle be made from nothing?

2.11.2

Use your knowledge of fundamental forces and exchange particles to explain how you are supported when you sit on a chair. Why is your sitting down not accompanied by flashes of light?

Tutorial 2.12 Particle Accelerators (Extension)

EDEXCEL syllabus, Scottish Higher syllabus and Irish Higher Syllabus

Contents

2.121 How do we probe the nucleus?

Much of the evidence for the structure of the nucleus comes from studies using **particle accelerators**. These machines make charged particles move at high speed, hence high kinetic energies, which are needed to investigate the structure of particles. The charged particles can be:

- Electrons.
- Protons (hydrogen ions);
- Alpha particles.

They are made to move by both attracting them and repelling them. The easiest particle to use is the electron. You will remember from GCSE that you charge objects by moving electrons. Protons never move. While you are not expected to recall details of particular particle accelerators, it's worth mentioning a couple.

2.122 Van der Graaff Generator

These machines can produce very high potential differences. The diagram below shows a typical machine you will find in a school physics laboratory (*Figure 80*).

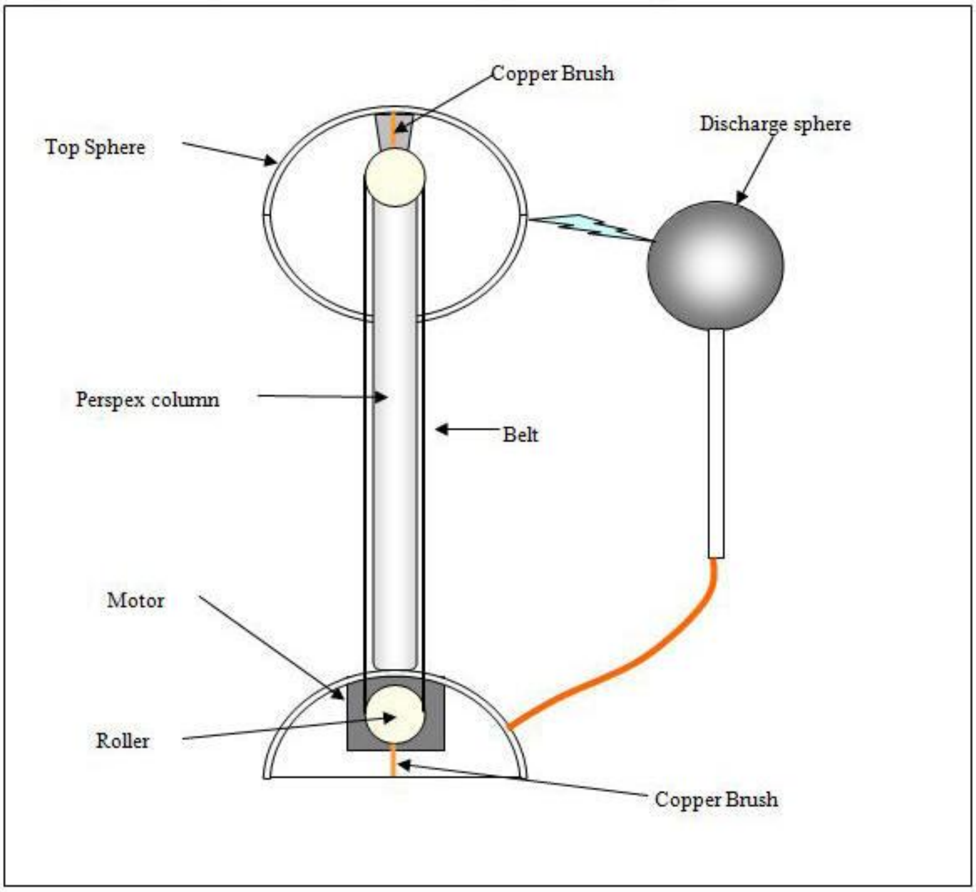


Figure 80 A school Van ger Graaff Generator

The machine pumps **electrons** upwards to the top sphere. The electrons crowd onto the top sphere and make the potential difference very large indeed. If the **breakdown voltage** of air, 3000 V/mm is exceeded, a spark will jump to the discharge sphere. The charge will be conducted back to the base through the wire.

When a big charge is being made on the top sphere, you can hear the motor slowing down as it has to work harder.

Some machines pump electrons **off** the top sphere, making it positive.

Large machines are filled with sulphur hexafluoride, a gas that is very good insulator. Very high voltages can be obtained.

2.123 The Cathode Ray Tube

This is another common accelerator, commonly found in old-style TV sets (*Figure 81*).

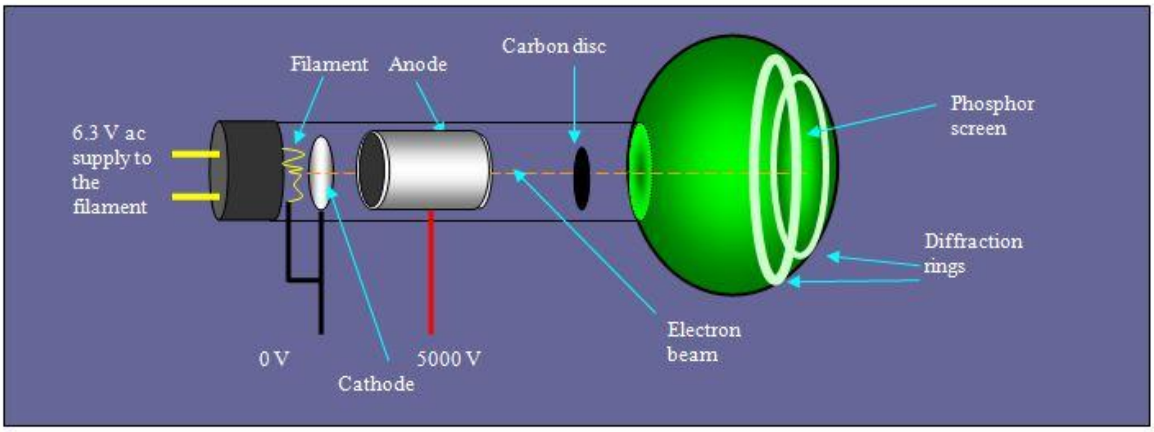


Figure 81 The cathode ray tube (CRT)

At its heart is the **electron gun**, in which current passes through a filament, which glows just like in a light bulb. The filament is connected to a source of electrons (the negative terminal of a high voltage source), called the **cathode**. Electrons are boiled off by a process of **thermionic emission**. They are attracted to a positively charged **anode**. Most hit the anode and go back to the source. Some go through a small hole in a narrow beam. (This was called the **cathode ray**.)

Since they are attracted by the very high potential difference, the electrons **accelerate**. Once they get to the anode (and pass out of the little hole), the electrons are moving very fast. All their energy is **kinetic**.

2.124 Energy of accelerated particles

The electron is a fundamental particle, with no substructure. All the energy of a moving electron is **kinetic**; there are no bonds to vibrate.

From GCSE physics, we know that:

Energy = charge × voltage

$$E = QV \text{ .... } \textit{Equation 1}$$

We also know that kinetic energy is given by:

$$E_k = \frac{1}{2}mv^2$$

.... *Equation 2*

So, we can equate the two equations and write:

$$QV = \frac{1}{2}mv^2$$

.........*Equation 3*

We can rearrange this to give:

$$v^2 = \frac{2QV}{m}$$

.... *Equation 4*

Therefore, since the Q term is the electronic charge, e (= 1.6×10^{-19} C), we can rewrite the equation as:

$$v^2 = \frac{2eV}{m}$$ .... *Equation 5*

The mass of an electron is 9.11×10^{-31} kg.

Worked example An electron is accelerated by a potential difference of 1500 volts. What is its speed as it passes through the electron gun?
Answer Use the Equation 5 above: $v = \sqrt{\frac{2eV}{m}} = \sqrt{\frac{2 \times 1.6 \times 10^{-19} \times 1500}{9.11 \times 10^{-31}}}$ **= 2.3×10^7 m s^{-1}**

This is 8 % of the speed of light, so you can see that the little brutes are moving like greased lightning.

Positively charged particles like hydrogen ions (protons) can be accelerated in a similar way. Chemists use a machine called a mass spectrometer that accelerates positively charged particles.

There is a limit to the speed to which particles can be accelerated. This maximum is the **speed of light** (3.0×10^8 m s^{-1}). As electrons get towards the speed of light, they start to turn their energy into mass (this may sound strange, but mass and energy are the same thing at this level). This is called a **relativistic** effect. The equation for kinetic energy that we know does not work at these speeds; another equation has to be used.

2.125 Larger Machines

The electron gun is the device that makes the electron microscope work. The electron microscope can resolve to about the diameter of an atom (10^{-10} m). A light microscope can resolve (pick out) objects down to about 0.5 mm, about the size of a bacterium. However, we need to have resolutions of 10^{-14} m and 10^{-15} m in order to resolve the nucleus. We can only achieve this by using powerful **particle accelerators**. The accelerator works by attracting a charged particle by a very large voltage and intense magnetic fields.

The **linear accelerator** is set out like this (*Figure 82*).

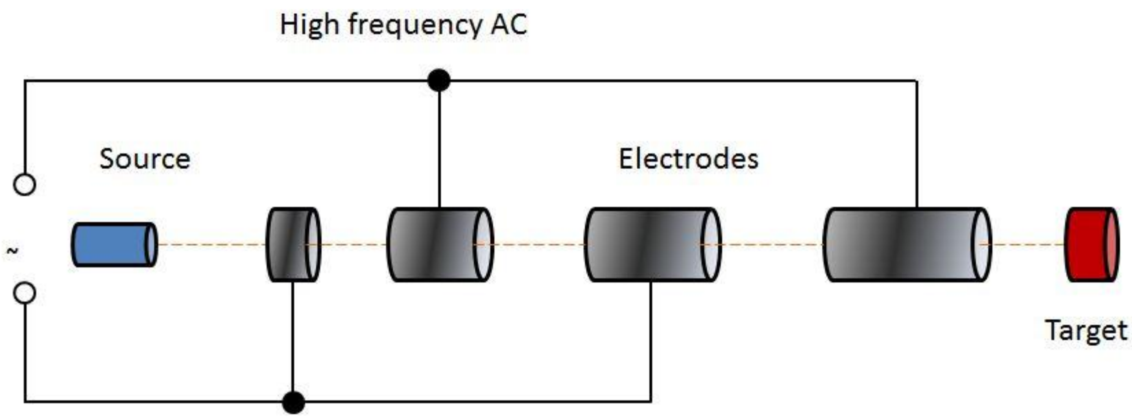


Figure 82 Linear Accelerator

Let's suppose that the source gives out electrons. The electrons are given off by thermionic emission, in the same way as the cathode ray tube. The electrons are attracted by the first electrode which is positive. They accelerate towards the positive electrode. As the electrons pass into the electrode, the polarity changes (as it's AC), so the electrode becomes negative, and the second electrode becomes positive. So, the electrons are repelled by the first electrode and attracted to the next electrode. As the they pass each electrode, the little brutes are given a kick up the backside. Therefore, they travel faster, towards the speed of light. The electrodes are longer the further up the accelerator they are. As the electrons get closer to the speed of light, relativistic effects occur, and the kinetic energy is turned into mass. Then the electrons strike the target.

Protons in the form of H^+ ions can be injected into the source. They have a higher mass, so can achieve the same levels of energy and momentum at a lower speed. Notes on the Cyclotron and the Synchrotron can be found in the A-level topic that covers Magnetic Fields.

Figure 83 A real linear accelerator (Photo by Alpinethread, published by Wikimedia Commons)

Accelerators are huge and massively expensive, as they require precision construction. The largest of these machines is to be found at **CERN** (Centre Europeènne de la Recherche Nucleaire) in Geneva, Switzerland. The Large Hadron Collider (LHC) lives in a circular tunnel, 27 km long. The detector has a mass of 14 000 tonnes, about the same size as a car ferry.

It has been so expensive to build and run that no one country could afford it. It a joint collaboration between states and universities. The World Wide Web grew from CERN from the need for universities to share the data from the experiments. A physicist, Tim Berners-Lee invented the language of the Web, **hypertext mark-up language** (html) after about 3 hours' work on Christmas Day in 1989 (an alternative to *The Sound of Music* on the box). And we know how useful it is.

The LCH has accelerated particles to an energy of 14 TeV (14×10^{12} eV).

Recent data from CERN suggested that neutrinos can travel faster than light. This has got physicists into a real twist, because we all know that nothing can travel faster than light, don't we? Physicists have always found neutrinos difficult to understand, and the idea of the little brutes going faster than light, well really! (Later it was found that there was some problem with cables between CERN and a remote site which led to a false conclusion, and some very red faces.)

2.126 Cockcroft and Walton Accelerator (Irish Syllabus, Higher Level)

This machine was named after the English physicist John Douglas Cockcroft (1897 - 1967) and the Irish physicist Ernest Thomas Sinton Walton (1903 - 1995). It is also referred to as a **voltage multiplier**. The machine looks like this (*Figure 84*)

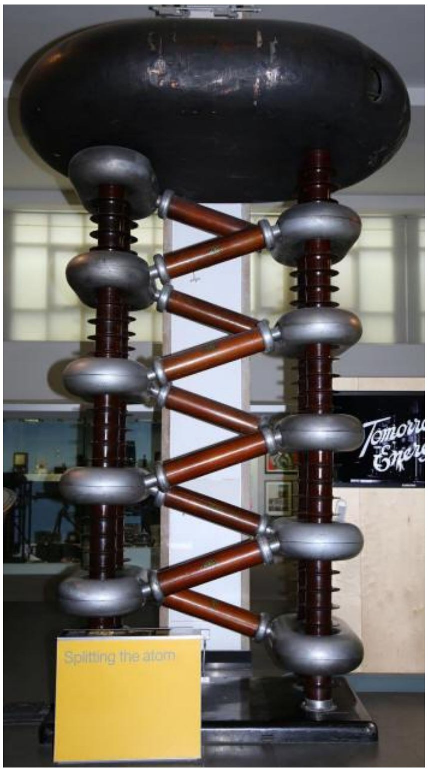


Figure 84 Cockcroft and Walton Accelerator (Image by Geni, Wikimedia Commons)

The voltage multiplier consists of two simple components, diodes and capacitors. You can see more about diodes and capacitors by clicking on the links. They are arranged in a **ladder network** like this (*Figure 85*).

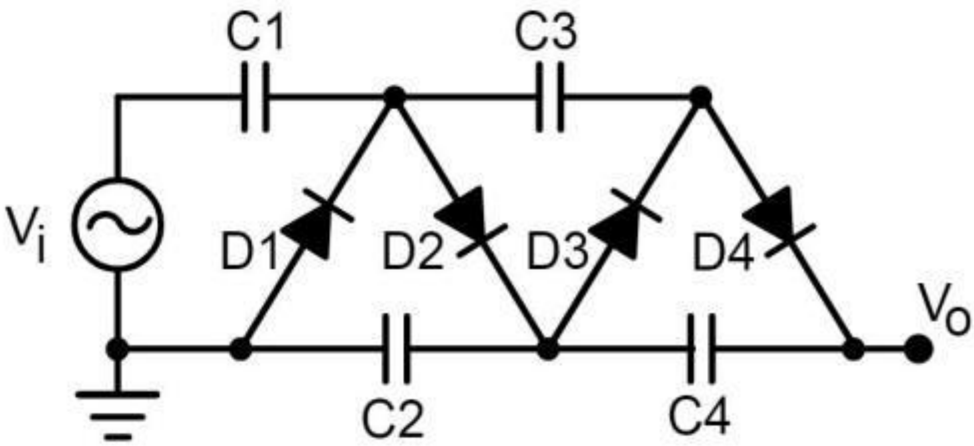


Figure 85 Schematic of a ladder network (Image by Chetvorno, Wikimedia Commons)

The ladder generates a high voltage direct current output from a low frequency alternating current or using pulsed direct current. Charged is pumped up the ladder. The circuit is, as a result, also called a **charge pump**. You could use a suitable transformer, but transformers are bulky and not easy to insulate at very high voltages. You can take a voltage off each rung of the ladder.

You do not need to know how it works, but if you are into electronics, this is what happens:

- When the input voltage V_i reaches its negative peak $-V_\mathrm{p}$, current flows through diode D1 to charge capacitor C1 to a voltage of V_p.
- When V_i reverses polarity and reaches its positive peak $+V_\mathrm{p}$, it adds to the capacitor's voltage to produce a voltage of $2V_\mathrm{p}$ on C1s righthand plate. Since D1 is reverse-biased, current flows from C1 through diode D2, charging capacitor C2 to a voltage of $2V_\mathrm{p}$.
- When V_i reverses polarity again, current from C2 flows through diode D3, charging capacitor C3 also to a voltage of $2V_\mathrm{p}$.
- When V_i reverses polarity again, current from C3 flows through diode D4, charging capacitor C4 also to a voltage of $2V_\mathrm{p}$.

The output voltage is twice the peak voltage multiplied by the number of stages N:

$$\mathrm{V}_{\mathrm{out}} = 2V_{\mathrm{p}} \times N$$

High voltage power supplies such as those in old CRT TV sets, and electrical insect killers use voltage ladders.

In 1932, Cockcroft and Walton made a machine that could generate a voltage up to 700 kV. It was used to accelerate **protons** with an energy of 700 keV into a target of **lithium**. For each proton that collided with a lithium nucleus, two helium atoms were given off according to the equation:

$$^{1}_{1}\mathrm{p} + {}^{7}_{3}\mathrm{Li} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He}$$

Each interaction gave off energy of 17.3 MeV.

The element lithium was transformed or **transmuted** into another element, **helium**. It was the first experiment of its kind and won the two physicists a Nobel Prize.

The splitting of a lithium atom by high-speed proton collision is NOT an example of nuclear fission.

Fission works by neutron collision with large nuclei.

Tutorial 2.12 Questions

2.12.1

A spark from a van der Graaff generator is 10 cm long. What voltage is this?

2.12.2

A proton of mass 1.67×10^{-27} kg and charge 1.6×10^{-19} C is accelerated by a potential difference of 4000 V. Calculate its speed.

Express this as a percentage of the speed of light ($c = 3.0 \times 10^{8}$ m s^{-1})

2.12.3

Work out the potential difference through which electrons have to be accelerated to travel at the speed of light.

2.12.4

How much energy in joules does a 14 TeV particle have?

Answers to Topic 2 Questions

Tutorial 2.01

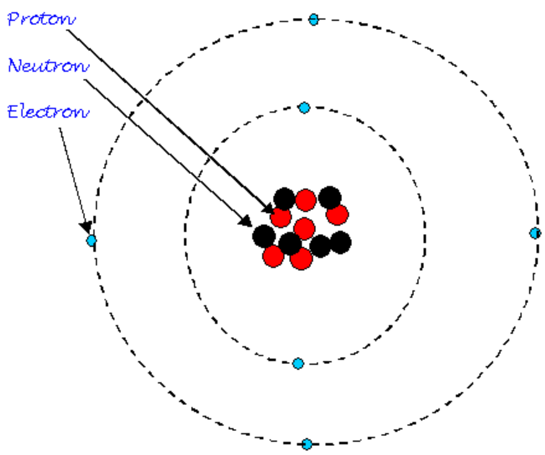
2.01.1

There are:

- 3 protons,
- 3 electrons,
- 4 neutrons

in a neutral lithium atom.

2.01.2



2.01.3

(a) 6e

(b) + 6 × 1.6 × 10^{-19} = **+9.6 × 10^{-19} C**

2.01.4

6 electrons, therefore the charge is -6e

This is -6 × 1.6 × 10^{-19} C = **-9.6 × 10^{-19} C**

2.01.5

Carbon-14 is an isotope of Carbon. Complete the table:	
Protons	6
Neutrons	8
Electrons	6
Write out carbon-14 in isotope form	$^{14}_{6}C$

Tutorial 2.02

2.02.1

The atom is neon (10 protons, 10 neutrons)

In isotope notation:

$$^{20}_{10}Ne$$

2.02.2

Yes.

The number of nucleons goes down by four.

The number of protons goes down by two.

2.02.3

(a)

$$^{19}_{8}O \rightarrow\, ^{19}_{9}F +\, ^{0}_{-1}e^{-} +\, ^{0}_{0}\overline{\nu}_{e}$$

(b)

$$^{212}_{84}Po \rightarrow\, ^{208}_{82}Pb +\, ^{4}_{2}He + energy$$

(c)

$$^{56}_{27}Co \rightarrow\, ^{56}_{26}Fe +\, ^{0}_{1}e^{+} + \nu_{e}$$

2.02.4

Total number of collisions for each particle = 4.8×10^{-13} J ÷ 5×10^{-18} J = **96000**

Distance travelled by alpha particle = 96000 ÷ 10^{5} cm^{-1} = 0.96 cm = **9.6 mm**

Distance travelled by beta particle = 96000 ÷ 10^{3} cm^{-1} = **96 cm**

Tutorial 2.03

2.03.1

Light shows wave behaviour:

- It can be polarised.
- It diffracts.
- It is reflected and refracted.

2.03.2

(a) $f = c/l$ = 3.0×10^{8} m s^{-1} ÷ 247 m = **1.2×10^{6} Hz**

(b) $l = c/f$ = 3.0×10^{8} m s^{-1} ÷ 2.0×10^{13} Hz = **1.5×10^{-5} m**. This is in the microwave region.

Answers should be to 2 significant figures.

2.03.3

A photon is a little packet of wave energy

(It has zero mass and travels at 3×10^8 m s^{-1}.)

2.03.4

$$E = hf$$

- E – energy per photon (J).
- h – Planck's constant, 6.63×10^{-34} J s (joule-seconds, NOT joules per second)
- f – frequency (Hz)

2.03.5

(a) $\lambda = c/f = 3 \times 10^8$ m s^{-1} ÷ 110.90×10^6 Hz = **2.71 m**

(b) $E = hf = 6.63 \times 10^{-34}$ J s × 110.90×10^6 Hz = **7.35×10^{-26} J**

(c) no of photons per sec = power ÷ energy per photon = 100 W ÷ 7.35×10^{-26} J

= 1.36×10^{27} s^{-1} **= 1.4×10^{27} s^{-1}** (2 s.f.)

2.03.6

Light as a wave:

It shows wave behaviour like:

- Refraction.
- Diffraction.
- Interference.
- Follows the wave equation.

Light as a particle:

- On a photographic film, particles of silver are deposited randomly to make up the picture.
- A certain amount of energy is needed to remove electrons from metals in the photoelectric effect. This cannot be explained using wave models.

Physicists use the photon model of light, where each photon is a packet of wave energy.

Tutorial 2.04

2.04.1

(a) Both particles are positively charged and are very close together

(b) a = 200 N ÷ 1.67 × 10^{-27} kg = **1.2 ×10^{29} m s^{-2}**

(c) The strong nuclear force.

2.04.2

Chemical reactions	Electromagnetic
Attraction between two planets.	Gravity
Beta decay	Weak
Holding the nucleus together	Strong

2.04.3

(a) A repulsive force

(b) The atoms are pushing apart because they are being forced together

(c) The atoms are just touching and are in equilibrium.

(d) C

(e) D The attractive force starts to decrease

(f) Electromagnetic

2.04.4

The electromagnetic force is mediated by virtual photons.

They are virtual because you cannot see them.

If you can see them, they are "off-task".

(a) If the objects are like charges, the photon is thrown directly to the other particle.

The other particle is throwing out another photon as well.

They exchange the photon, and are pushed apart.

(b) The photons can be regarded as a lasso.

Each particle lassoes the other oppositely charged particle in towards itself.

This is a very limited model.

What happens in reality is not well understood.

Tutorial 2.05

2.05.1

100 eV	**$100 \times 1.6 \times 10^{-19} = 1.6 \times 10^{-17}$ J**
100 MeV	**1.6×10^{-11} J**
10 GeV	**1.6×10^{-9} J**

2.05.2

100 eV	$v^2 = 2\ Ek/m$ = (2 × 1.6 × 10^{-17} J) ÷ 9.11 × 10^{-31} kg
	v = 5.9 × 10^6 m s^{-1}
10 GeV	$v^2 = 2\ Ek/m$ = (2 × 1.6 × 10^{-9} J) ÷ 9.11 × 10^{-31} kg
	v = **5.9 × 10^{10} m s^{-1}** (which is not possible)

2.05.3

a)

$E = mc^2$ = 1.67 × 10^{-27} kg × (3 × 10^8 m s^{-1})^2 = 1.50 × 10^{-10} J

Convert to eV: E = 1.50 × 10^{-10} J ÷ 1.6 × 10^{-19} = **939 MeV/c^2**

(b)

Convert the 126 GeV into joules

E = 126 × 10^9 eV × 1.60 × 10^{-19} J eV^{-1} = 2.016 × 10^{-8} J

$m = E/c^2$ = 2.016 × 10^{-8} J ÷ (3.0 × 10^8 m s^{-1})^2 = **2.2 × 10^{-25} kg**

(c)

Ratio = 2.24 × 10^{-25} kg ÷ 1.67 × 10^{-27} kg = **134** times the mass of a proton (about the mass of a caesium atom).

2.05.4

a. The two particles annihilate.

b. Rest energy = 1.022 MeV (did you remember that there are 2 particles?)

Energy of each photon = 1.022 ÷ 3 = 0.341 MeV

Energy of each photon = 0.341 × 10^6 eV × 1.6 × 10^{-19} = **5.456 × 10^{-14} J**

c. λ = (6.63 × 10^{-34} J s × 3 × 10^8 m s^{-1}) ÷ 5.456 × 10^{-14} J

λ = 3.6 × 10^{-12} m (gamma)

2.05.5

Annihilation happens when a particle and anti-particle collide.

Two gamma photons are formed.

The photons each have the energy of the particle, as the particle masses are made into energy.

Energy and momentum are conserved.

2.05.6

a. Two products each of rest mass 0.5511 MeV

$2 \times 0.511 =$ **1.022 MeV**

b. $\lambda = (6.63 \times 10^{-34}\ \text{J s} \times 3.0 \times 10^{8}\ \text{m s}^{-1}) \div (2 \times 8.176 \times 10^{-14}\ \text{J})$

$\boldsymbol{\lambda = 1.2 \times 10^{-12}\ \text{m}}$

c. $0.511\ \text{MeV} = 0.511 \times 10^{6} \times 1.6 \times 10^{-19} = 8.176 \times 10^{-14}\ \text{J}$

Mass $= 8.176 \times 10^{-14}\ \text{J} \div 9.0 \times 10^{16} =$ $\boldsymbol{9.1 \times 10^{-31}\ \text{kg}}$

Tutorial 2.06

2.06.1

τ^+, $Q = +1$, $L_\varepsilon = 0$, $L_\mu = 0$ $L_\tau = -1$.

2.06.2

$$e^- + e^+ \rightarrow \mu^+ + \mu^-$$

Q: -1 + +1 → +1 + -1 (number is conserved as 0 = 0);

L_ε: +1 + -1 → 0 + 0 (number is conserved)

L_μ: 0 + 0 → -1 + -1 (number is conserved)

L_τ: 0 + 0 → 0 + 0 (number is conserved)

The interaction can happen.

2.06.3

The electron neutrino has a rest energy of 2.2 eV = 2.2 eV × 1.6 × 10^{-19} J eV^{-1} = 3.52 × 10^{-19} J

m = 3.52 × 10^{-19} J ÷ (3.0 × 10^{8} m s^{-1})^{2} = **3.91 × 10^{-36} kg** (≈ 4.0 × 10^{-36} kg)

Tutorial 2.07

2.07.1

A hadron is a particle feels the strong nuclear force.

2.07.2

Q = +2/3 × 1.6 × 10^{-19} C = **1.067 × 10^{-19} C**

Tutorial 2.08

2.08.1

down, anti-up

2.08.2

Baryon number for a quark is +1/3

Baryon number for antiquark is -1/3

Baryon number for meson = +1/3 + -1/3 = 0

2.08.3

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

Q: +1 = +1 + 0

B: 0 = 0 + 0

L: 0 = -1 + +1

Interaction will proceed as conservation numbers are conserved.

Tutorial 2.09

2.09.1

(a) up, down, down (udd)

(b) Q = 2/3 + -1/3 + -1/3 = 0

(c) B = 1/3 + 1/3 + 1/3 = 1

(d) Neutron decays to a proton, and electron, and an electron antineutrino (beta minus decay).

2.09.2

(a) Same charge (0), same mass.

(b) The anti-neutron is made up of anti-up, anti-down, anti-down (udd) compared with up, down, down (udd) for a neutron.

(c) An antiproton, a positron, and an electron neutrino.

2.09.3

(a) 1 strange quark

(b) Strange, up, up (suu) (-1/3 + 2/3 + 2/3 = 1)

(c) Anti-strange, anti-up, anti-up (suu)

(d) The sigma minus baryon has a quark composition of strange, down, down (sdd) while the anti-baryon has anti-strange, anti-up, anti-up (suu).

Tutorial 2.10

2.10.1

Energy

Momentum

Charge

Baryon Number

Lepton Number

2.10.2

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$

Q: +1 → +1 + 0

B: 0 → 0 + 0

Lμ: 0 → -1 + +1

All quantum numbers are conserved, so the interaction will happen.

2.10.3

$$\Lambda^{0} \rightarrow \mathrm{p}^{+} + \pi^{-}$$

Q: 0 → +1 + -1

B: 1 → 1 + 0

L: 0 → 0 + 0

All quantum numbers are conserved, so the interaction will happen.

2.10.4

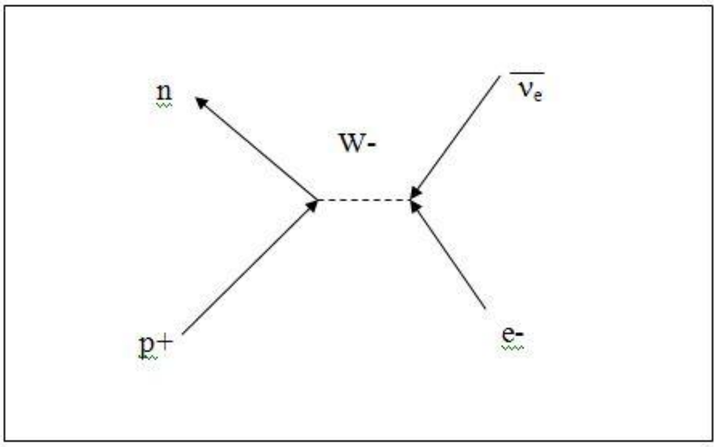
The lepton number of the neutron is 0.

The lepton number of the proton, electron, and the electron anti-neutrino is 0, +1, and -1 respectively.

They all add up to 0 so the interaction can proceed.

If the electron antineutrino was a neutrino, the lepton number would not be conserved.

2.10.5



Interaction:

$$p^+ + e^- \rightarrow n + \overline{\nu_e}$$

Q: +1 + -1 → 0 + 0 Yes

B: +1 + 0 → +1 + 0 Yes

Le: 0 + +1 → 0 + -1 No

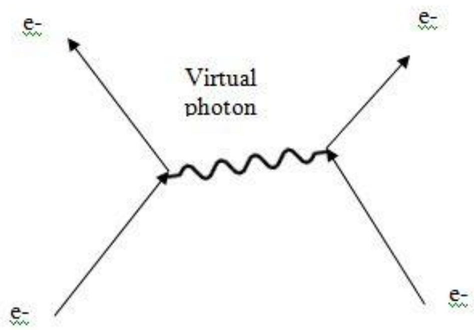
The electron lepton number is not conserved. Therefore, the interaction cannot proceed.

If the electron antineutrino was a neutrino, the lepton number would be conserved.

The **W+ boson** transfers positive charge from the proton.

The muon and tau lepton numbers are not shown.

2.10.6



Tutorial 2.11

2.11.1

Mass and energy is interchangeable at this level.

Heisenberg's Uncertainty Principle allows energy to be borrowed in very short time frame.

This energy is borrowed from other particles.

A new very short-lived particle is formed.

The energy is returned to the particles.

2.11.2

When you sit down, your weight is balanced by a support force from the chair.

The support force comes from atoms in the chair and your bottom repelling each other.

The repulsion comes from the electron shells interacting between the atoms.

The electromagnetic force is responsible for the interactions between electrons.

The electromagnetic force is mediated by the transfer of virtual photons.

You do not see a shower of photons because they are virtual, lasting only a short time.

If we could see the photons, they would not be involved in the interaction.

Tutorial 2.12

2.12.1

Break down voltage = 3000 V mm^{-1}

Voltage = 3000 V mm^{-1} × 100 mm = **300 000 V**

2.12.2

$$v^2 = \frac{2QV}{m}$$

$v^2 = \frac{2 \times 1.6 \times 10^{-19}\ \text{C} \times 4000\ \text{V}}{1.67 \times 10^{-27}\ \text{kg}} = 7.66 \times 10^{11}\ \text{m}^2\ \text{s}^{-2}$

$v = \sqrt{(7.66 \times 10^{11})}$ = **8.8×10^5 m s^{-1}**

As a percentage of c, $v = (8.8 \times 10^{5}\ \text{m s}^{-1} \div 3.0 \times 10^8\ \text{m s}^{-1}) \times 100 =$ **c**

2.12.3

$V = mv^2/2e = (9.11 \times 10^{-31}\ \text{kg} \times (3.0 \times 10^8\ \text{m s}^{-1})^2) \div (2 \times 1.6 \times 10^{-19}\ \text{C})$

= 2.56×10^5 V

In practice, it is not possible to get electrons to reach the speed of light. Due to relativistic effects, the kinetic energy is converted into mass.

2.12.4

14 TeV = 14×10^{12} eV $\times 1.6 \times 10^{-19}$ = **2.24×10^{-6} J**

It may not seem a lot, but at the particle level, this is enormous.