3.2 Particles and Radiation

3.2.1 Particles

3.2.1.1 Constituents of the Atom

Content

- Simple model of the atom, including the proton, neutron and electron. Charge and mass of the proton, neutron and electron in SI units and relative units.
- The atomic mass unit (amu) is included in the A Level Nuclear physics section.
- Specific charge of the proton and the electron, and of the nuclei and ions.
- Proton number Z, nucleon number A, nuclide notation.
- Students should be familiar with the $^A{}_Z X$ notation.
- Meaning of isotopes and the use of isotopic data.

So a simple model of the atom...

From Rutherford's experiments we understand that the atom consists of positively charged protons with neutral neutrons in one place, called a nucleus. The nucleus sits in the middle of the atom with negatively charged electrons orbiting it.

Constituent	Charge (C)	Relative Charge	Mass (kg)	Relative Mass
Proton	$+ 1.6 \times 10^{-19}$	+1	1.67×10^{-27}	+1
Neutron	0	0	1.67×10^{-27}	+1
Electron	$- 1.6 \times 10^{-19}$	-1	9.11×10^{-31}	1/2000 (Negligible)

Specific Charge

Specific charge is the charge to mass ratio of an atom/ion or other mass. The equation for it therefore, is: Specific Charge = Charge/Mass.
The charge on an atom will always be 0, so if an atom loses two electrons, that is $2 \times (1.6 \times 10^{-19})$ of charge lost, or -2e. Therefore, the specific charge of the newly formed ion would be -2e divided by its mass. In short, if an atom loses an electron it will lose 1e (1.6×10^{-19}), and if it gains an electron, it will gain 1e.
The electron has the highest specific charge; the neutron has the lowest.

Specific Charge Calculations

- Proton = $+1.6 \times 10^{-19}/1.67 \times 10^{-27} = 9.58 \times 10^{7}$ C/kg or Ckg^{-1}
- Electron = $1.6 \times 10^{-19}/9.11 \times 10^{-31} = 1.76 \times 10^{11}\ Ckg^{-1}$
- $^7{}_3Li$ Nucleus = The nucleus has 3 protons and 4 neutrons, neutrons have a charge of 0 so the charge of the nucleus is 3 x the charge of the proton. It has a total of 7 nucleons (neutrons and protons) so therefore 7 x the mass of the neutron/proton.
  Equals $3 \times 1.6 \times 10^{-19}/7 \times 1.67 \times 10^{-27} = 4.1 \times 10^{7}\ Ckg^{-1}$

- ${}^{7}_{3}Li$ atom that has lost two electrons = Charge of the ion is +2e (2 x 1.6 x 10^{-19}) as it has lost two negatively charged electrons, divided by the mass of the nucleus plus the mass of the 1 remaining electron. +2e / (7 x 1.67 x 10^{-27}) + (1 x 9.11 x 10^{-31}) =2.7 x 10^{7} Ckg^{-1}.

Notation

${}_{Z}^{A}X$ is the notation where Z is the proton number, and A is the nucleon number. Proton number is also equal to the number of electrons in an uncharged atom. A-Z = the number of neutrons.

Isotopes

An isotope has the same number of protons and electrons, however a different number of neutrons, thus behaving the same chemically. For example, Chlorine ${}^{35.5}_{17}Cl$ where 35.5 is the average nucleon number of the isotopes.

3.2.1.2 Stable and Unstable Nuclei

Content

- The strong nuclear force; its role in keeping the nucleus stable; short-range attraction up to 3fm, very-short range repulsion closer than approximately 0.5fm.
- Unstable nuclei; alpha and beta decay.
- Equations for alpha decay, β^- decay including the need for the neutrino.
- The existence of the neutrino was hypothesized to account for conservation of energy in beta decay.

Opportunities for skills development

- Demonstration of the range of alpha particles using a cloud chamber, spark counter or Geiger counter.
- Use of prefixes for small and large distance measurements.

The Strong Force

The strong nuclear force is one of the four fundamental forces, the other three being the Weak Nuclear, Electromagnetic and Gravity. The strong nuclear force only acts at extremely short-range attraction from 0.5fm to 3fm (fm=femtometre=10^{-15}). Its effects slowly become negligible as the distance increases above 3fm, and repulsion occurs at distances lower than 0.5fm. It acts within the nucleus to overcome the electrostatic repulsion that usually occurs between protons of the same charge, and therefore keeps the nucleus stable by keeping protons and neutrons together.

Alpha and Beta Decay

- Alpha Decay is the omission of an alpha particle from the nucleus of an atom, which has the same chemical composition of a helium nucleus. It is comprised of 2 neutrons and 2 protons. Its notation is ${}_2^4\alpha$. Alpha decay occurs in proton rich nuclei, where the ratio of protons to neutrons is too high, for example Polonium – 210. It has 126 neutrons and 84 protons, a ratio of 1.5 to 1. It omits an alpha particle to leave 124 neutrons to 82 neutrons and thus the ratio becomes 1.51 to 1.

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

- β^- decay is the omission of an electron from an unstable nucleus. Its notation is ${}_{-1}^{0}\beta^-$. It happens when a neutron changes to a proton in the nucleus, the beta particle is released as a result of this. Also, an antiparticle with no charge, called an antineutrino The symbol for an antineutrino is $\bar{\nu}$
Due to the fact a neutron changes to a proton, the atomic number increases by 1, but nucleon number stays the same.

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

The antineutrino is crucial to conserving energy within beta decay. It also ensures conservation of lepton number, in β^- decay an antineutrino is released, and in β^+ decay a neutrino is released. However this is a concept you will cover later in the specification. The electron neutrino was first theorised in 1930 by Wolfgang Pauli to account for missing energy and momentum in β^- decay, and then discovered in 1956 by Clyde Cowan and Frederick Reines. Its mass is negligible, with no charge either, purely energy and a small momentum to converse these values in the equation.

3.2.1.3 Particles, Antiparticles and Photons

Content

- For every particle, there is a corresponding antiparticle.
- Comparison of particle and antiparticle masses, charge and rest energy in MeV.
- Students should know the positron, antiproton, antineutron and antineutrino are the antiparticles of the electron, proton, neutron and neutrino respectively.
- Photon model of electromagnetic radiation, the Planck constant.
- $E = hf = hc/\lambda$.
- Knowledge of annihilation and pair production and the energies involved.
- The use of $E=mc^2$ is not required in calculations.

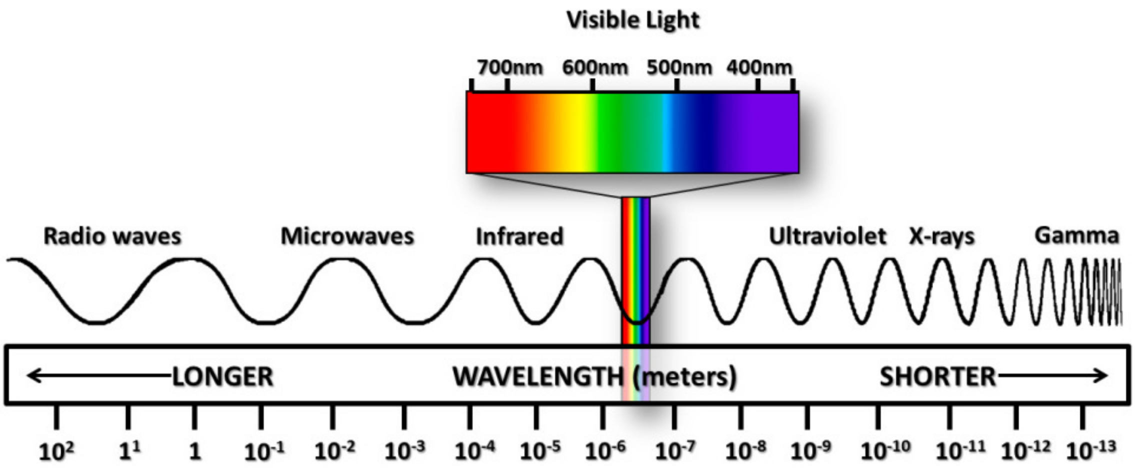
Opportunities for skills development

- Detection of gamma radiation
- Students could determine the frequency and wavelength of the two gamma photons produced when a 'slow' electron and a 'slow' positron annihilate each other.
- The PET scanner could be used as an application of annihilation.

Antiparticles have the same mass, opposite charge, and the same rest energy in MeV. They also have opposite baryon number/lepton number, strangeness, and the opposite quark composition (concepts that will be studied later on).
Paul Dirac was the first person to propose the existence of a particle of equal mass to an electron, but opposite charge, a particle called the positron. He proposed this in 1928.
The main antiparticles are as follows.

Particle	**Antiparticle**
Electron	Positron
Proton	Antiproton
Neutron	Antineutron
Neutrino	Antineutrino

Photon model of Electromagnetic Radiation and the Planck Constant



Max Planck revolutionised the way we perceive light, he said that light could be released as 'packets' of energy. Einstein named these packets photons, and said that energy could be carried in these photons where the energy was equal to E=hf. E equals energy of a photon, h equals Planck's constant (6.63 x 10^{-34}) and f equals frequency of the photon. Since c=λf, then if you substitute c/ λ = f into E=hf then you also get the equation E=hc/λ. Essentially Planck's constant links the amount of energy a photon carries with the frequency of its electromagnetic wave. Although you just need to be able to use h in equations, and are given the value of h in the data and formulae sheet.

Annihilation and Pair Production

Annihilation

Whenever a particle and antiparticle meet, they will annihilate each other, producing two photons where the mass of the particles is converted into energy. An example of this is when an electron and positron annihilate, they produce two photons of energy with energy equal to their rest mass energies and any other energy the particles may have had.

Pair Production

Pair production is where energy is converted into mass, the opposite of annihilation. A single photon of energy is converted into a particle-antiparticle pair. This can only happen if the photon has enough mass-energy to produce the particle-antiparticle pair, and any leftover energy is converted into kinetic energy for the particles to travel. Pair production occurs spontaneously; however, it must occur in very close proximity to a nucleus (the nucleus helps to conserve momentum) Furthermore, if pair production was to occur in a magnetic field, then the particle-antiparticle pair would move in opposite directions if they are oppositely charged, i.e. an electron and positron.

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Question:

Give one reason why the photon could not produce a single electron instead of an electron and a positron. (pair production)

Answer:

- Conservation law stated (charge or lepton number must be conserved)
- Shown to be true eg lepton number +1 -1 = 0

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Question:

Fig. 6.3 shows a positron–electron pair being produced by a gamma photon in a cloud chamber. There is a uniform magnetic field acting perpendicularly into the diagram, shown by the shaded area.

Add a line to **Fig. 6.3** to show the path of the incoming gamma photon. Explain why the gamma photon left **no** track in the cloud chamber, and why the positron and electron follow the paths shown in **Fig. 6.3**.

Answer:

- Straight line diagonally up to point of pair creation roughly bisecting the 'V'□
- Gamma is uncharged/not very ionising□
  e^+ and e^- have opposite charges (so qvB has opposite sign, or r = mv/BQ has opposite charge)
- so they curve in opposite directions□
- paths are spirals **or** radius of paths becomes less as they go on (because) the positron and electron are slowing down
- due to energy loss through ionising the air particles (which is why you can see the tracks)□

Question:

Fig. 6.4 shows an annihilation in a cloud chamber. There is a uniform magnetic field acting perpendicularly into the diagram, shown by the shaded area. An antiproton enters near the bottom and collides with a stationary proton. The annihilation creates eight hadrons numbered 1 – 8 in **Fig. 6.4.**

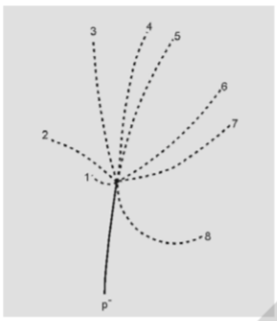


Fig. 6.4

Explain how the tracks of the particles in **Fig. 6.4** show that charge is conserved in this reaction.

Answer:

total charge before = 0 (p^+ and p^-) ✓

4 hadron tracks curve clockwise and 4 anticlockwise, so for every + charge there is a - charge✓

3.2.1.4 Particle Interactions

Content

- Four fundamental interactions: gravity, electromagnetic, weak nuclear, strong nuclear. (The strong nuclear may be referred to as the strong interaction.)
- The concept of exchange particles to explain forces between elementary particles.
- Knowledge of the **gluon, Z^0 and graviton will not be tested**.
- The electromagnetic force; virtual photons as the exchange particle.
- The weak interaction limited to β^- and β^+ decay, electron capture and electron-proton collisions; W^+ and W^- as the exchange particles.
- Simple diagrams to represent the above reactions or interactions in terms of incoming and outgoing particles and exchange particles.

Opportunities for skills development

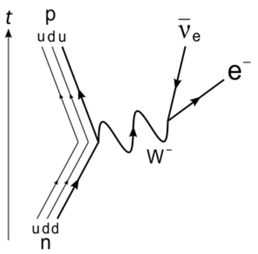
- Momentum transfer of a heavy ball thrown from one person to another.

Fundamental Forces and their Exchange Particles

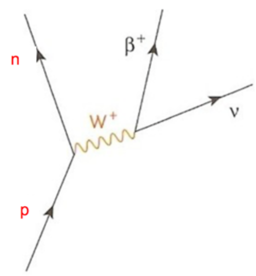
Force	**Exchange Particles**	**Range**
Strong Interaction	Gluons/Pions	About 10^{-15} metres
Weak Interaction	Z^0, W^+, W^-	About 10^{-17} metres
Electromagnetic	Virtual Photon (γ)	Infinite
Gravity	Gravitons	Infinite

If you look at the virtual photon, the exchange particle for the electromagnetic force, its purpose is to carry electromagnetic force between charged particles. Particles with charges either attract or repel each other by exchanging particles called virtual photons. The W and Z bosons involved in the weak interaction, and when particles decay, the W and Z bosons take the charge and energy and almost instantaneously decay into whatever is being produced. The gluon and gravitons are involved in the strong interaction and gravity, however will not be tested.

β^- and β^+ decay

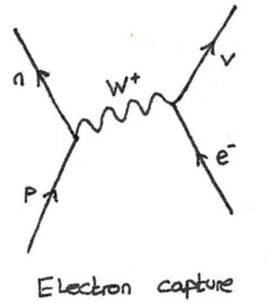


This is beta minus decay. An electron and anti electron neutrino is produced. In beta plus decay, a proton decays into a neutron and W^+ boson, which then decays instantaneously into a positron and electron neutrino. This is shown below



Electron Capture and Electron-Proton Collisions

Electron capture is where unstable atoms become more stable. They draw an electron from the atom's inner shell into the nucleus. Here it causes combines with a proton to form a neutron, which causes the production of an electron neutrino as well (to conserve energy and momentum). The picture below illustrates an electron proton collision, producing a neutron and electron neutrino. The v on the diagram should have a subscript 'e' on it.



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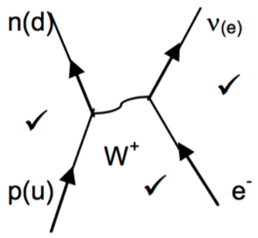
'Explain what is meant by electron capture.'

- An atomic/orbital electron interacts with a proton in the nucleus (via the weak interaction), which forms a neutron (u quark changes to d quark) and also forms an electron neutrino.

'In the space below draw a Feynman diagram representing electron capture.'



3.2.1.5 Classification of Particles

Content

- Hadrons are subject to the strong interaction.
- The two classes of hadrons:
  - Baryons (proton, neutron) and antibaryons (antiproton and antineutron)
  - Mesons (pion, kaon).
- Baryon number as a quantum number
- Conservation of baryon number
- The proton is the only stable baryon into which other baryons eventually decay.
- The pion is the exchange particle of the strong nuclear force.
- The kaon as a particle that can decay into pions.
- Leptons: electron, muon, neutrino (electron and muon types only) and their antiparticles.
- Lepton number as a quantum number; conservation of lepton number for muon leptons and for electron leptons.
- The muon as a particle that decays into the electron.
- Strange particles**.**
- Strange particles as particles that are produced through the strong interaction and decay through the weak interaction (e.g. kaons)
- Strangeness (symbol s) as a quantum number to reflect the fact that strange particles are always created in pairs.
- Conservation of strangeness in strong interactions.
- Strangeness can change by 0, +1 or -1 in weak interactions.
- Appreciation that particle physics relies on the collaborative efforts of large teams of scientists and engineers to validate new knowledge.

Opportunities for skills development

- Use of computer simulations of particle collisions.
- Cosmic ray showers as a source of high energy particles including pions and kaons; observation of stray tracks in a cloud chamber; use of two Geiger counters to detect a cosmic ray shower.

Hadrons, Baryons and Mesons

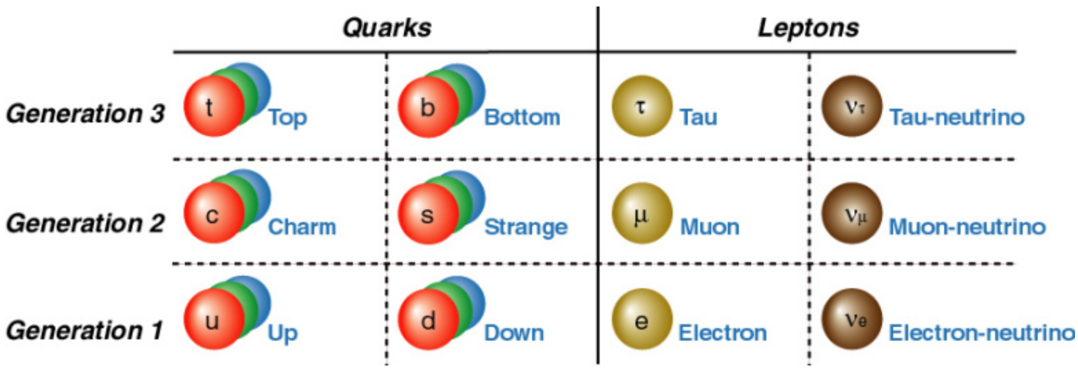
The building blocks of matter are (as far as we know) leptons and quarks, they are what is called fundamental (cannot be subdivided into smaller constituents). There are two main classifications of particles, hadrons and leptons. Leptons are fundamental as I mentioned, whereas hadrons are made of quarks. There are six types of quarks, however this course only requires knowledge of three, the up, down and strange quark. Each quark has its own respective charge, strangeness, and baryon number, this data is all given in the data and formula sheet. Each quark also has an antiquark, which has opposite charge, strangeness and baryon number. The other differentiation between hadrons and leptons are that leptons are not subject to the strong nuclear force, whereas hadrons are.

There are many different hadrons, so to make it easier, there are smaller groups within the classification of hadrons. These two groups are baryons (protons, neutrons) and mesons (pions, kaons). Baryons consist of a combination three quarks and antiquarks, whereas mesons are comprised of a quark antiquark pair. Hadrons all have a baryon number; this number must be an integer; each quark has a baryon number of 1/3. Their charge must also be of an integer, i.e. a proton made up of uud quarks has a charge of 1 and baryon number 1. Baryon number is therefore a quantity given to quarks, and must **always** be conserved in interactions.

The only stable baryon is the proton; all other baryons will eventually decay into the proton. In terms of mesons, the pion is the exchange particle for the strong force, and the kaon is a particle that can eventually decay into a pion.

Leptons

As mentioned before, leptons are subject to the strong interaction, and are fundamental. The leptons required for the course are the electron, muon and the neutrino. The electron and muon have their own respective neutrinos, as well as their own antiparticles. The electrons being the positron, the muons being the antimuon. Lepton number must also always be conserved, and each type must be conserved in its own right. For example in an interaction if there is an electron of lepton number 1 on one side, and a muon neutrino on the other side with lepton number 1, then conservation of lepton number will not be satisfied as it would have to be an electron neutrino to be satisfied. Therefore, within each family of lepton, lepton number must be conserved. The muon will eventually decay into the electron, and is around 200x heavier than the electron. The different lepton families are shown below.



Strangeness

Strangeness is a quantity given to the aptly named strange quark, and strangeness refers to the amount of strange quark content in a given hadron. Before the discovery of quarks, Murray Gell-Mann **(He was the person that discovered and named these elementary particles "quarks" because of the book "Finnegan's Wake" he had read which included the line, "Three quarks for Muster Mark…".)** had said that a new set of particles that had been discovered, had a conserved quantum number called "strangeness", this was purely put in for bookkeeping reasons, just to explain the decay of the new particles into the old familiar particles. However when the quark theory was introduced, this property was associated with a new particle, the strange quark.

Strange particles are produced through the strong interaction and decay via the weak interaction i.e. the kaon into the pion, they are also always produced in pairs. Strangeness must always be conserved in strong interactions, however does not need to be in the weak interaction. Strangeness can also only change by -1, 0 or +1 in weak interactions, this type of knowledge is embedded into questions so is worth keeping fresh in your mind as it may be difficult to realise at first sight.

Appreciation that particle physics relies on the collaborative efforts of large teams of scientists and engineers to validate new knowledge.

3.2.1.6 Quarks and Antiquarks

Content

- Properties of quarks and antiquarks: charge, baryon number and strangeness.
- Combinations of quarks and antiquarks required for baryons (proton and neutron only), antibaryons (antiproton and antineutron only) and mesons (pion and kaon only)
- Only knowledge of up (u), down (d) and strange (s) quarks and their antiquarks will be tested.
- The decay of the neutron should be known.

Properties of Quarks and Antiquarks

Type	Charge	Baryon Number	Strangeness
u	+2/3e	+1/3	0
d	-1/3e	+1/3	0
s	-1/3e	+1/3	-1

Combinations of Quarks

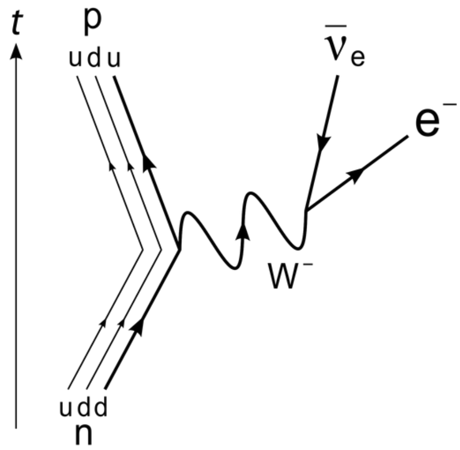
As you already know, quarks are fundamental particles that make up hadrons. Their combinations consist of two quarks (mesons) and three quarks (baryons), a pentaquark composition was supposedly found but there was not enough evidence for this, so those are the two groups of quarks that we know of. The combinations of quarks that make up various particles are as follows;

Particle	Quark Combination	Baryon Number	Strangeness	Charge
Proton (p)	uud	1	0	1
Neutron (n)	udd	1	0	0
Antiproton ($\bar{p}$)	$\bar{u}\bar{u}\bar{d}$	-1	0	-1
Antineutron ($\bar{n}$)	$\bar{u}\bar{d}\bar{d}$	-1	0	0
Neutral Pion (π^0)	$d\bar{d}$/$u\bar{u}$	0	0	0
Positive Pion (π^+)	$u\bar{d}$	0	0	+1
Negative Pion (π^-)	$\bar{u}d$	0	0	-1
Neutral Kaon (K^0)	$s\bar{d}$/$\bar{s}d$	0	-1/+1	0
Positive Kaon (K^+)	$u\bar{s}$	0	+1	+1
Negative Kaon (K^-)	$\bar{u}s$	0	-1	-1

The protons, neutrons, antiprotons and antineutrons are straightforward in the fact that they only have one possible combination. However, the Pion and Kaons have various different combinations. First of all, you can get a positive, neutral and negative version of the Pion and Kaon. Then, you are also able to get more than one possible combination for the neutral kaon and pion. For the pion it can be either an antidown-down combination or antiup-up combination. This is because both combinations give exactly the same baryon number, strangeness and charge, i.e. exactly the same particle, but just with different quarks. This is not the same for the positive and negative versions of the Pions and Kaons however, that have only one possible combination. You are able to work out their combinations by knowing that Kaons are the only mesons that can be strange.

For example, if you were given a neutral Kaon in a question then knowing that Kaons are strange particles, there must be a strange quark present. Also knowing that Kaons are composed of 2 quarks, with a baryon number of 0, and that neutral Kaons have a charge of 0, you can work out that the combination of quarks must be strange with an antidown or vice versa.

Decay of the Neutron



The neutron will decay into a proton, as well as producing an electron and anti electron neutrino. The exchange particle for this is the W^- boson. This is because the neutron is neutral, and the proton produced has a charge of +1, so to conserve charge, the charge of the exchange particle needs to be -1. This exchange particle then almost instantaneously decays into the electron and anti electron neutrino. The reason an anti electron neutrino is produced is to conserve lepton number, as the original lepton number is 0, so the final lepton number should be 0. Lepton number of the electron is +1 and of the anti electron neutrino is -1, so it is conserved.

You can also look at the decay in terms of quarks. A down quark changes to an up quark to produce a proton (uud) from the neutron (udd). Questions may give you decays or interactions/diagrams in terms of quarks *or* particles so you need to be familiar with both.

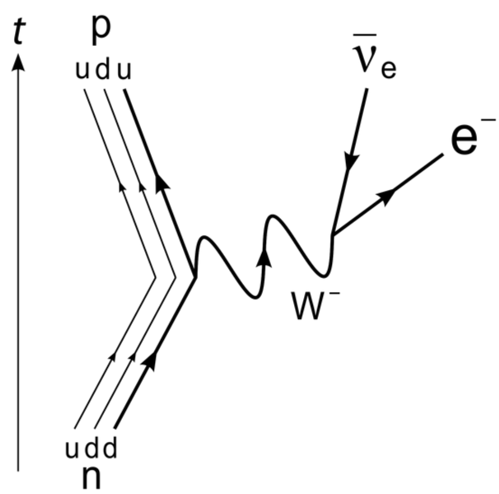
3.2.1.7 Application of Conservation Laws

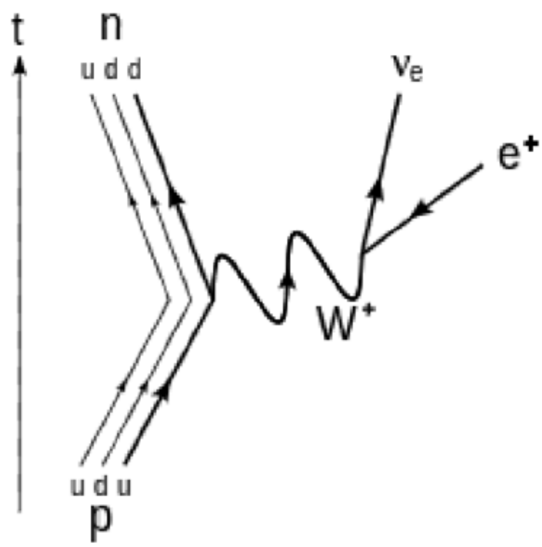
Content

- Change of quark character in β^- and in β^+ decay.
- Application of conservation laws for charge, baryon number, lepton number and strangeness to particle interactions. The necessary data will be provided in questions for particles outside those specified.
- Students should recognise that energy and momentum are conserved in interactions.

Change of quark character in β^- and β^+ decay

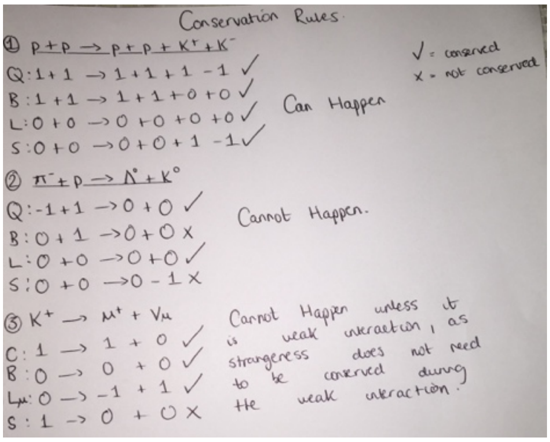
The first diagram shows β^- decay, and the second shows β^+ decay.





Application of conservation laws for charge, baryon number, lepton number and strangeness to particle interactions. The necessary data will be provided in questions for particles outside those specified.

When applying conservation rules, you need to consider all of the different properties that need to be conserved. The main ones will be charge, baryon number, lepton number and strangeness. If you write these properties down the side, then write out the various amounts of each, you can see if the property has been conserved. For example in number one, the relative charge on the proton is +1 so overall charge initially was +2. The charge after the interaction was also +2 so charge had been conserved. If all properties are conserved then the interaction is possible, and vice versa.



Energy and Momentum

Energy and momentum are **always** conserved in interactions. You should remember facts like these, as well as charge, baryon number, lepton number and others being conserved as questions are likely to come up on this topic.

Summary of 3.2.1

Usually in this section of particle physics, questions asked are short answer questions, purely based on recall. Therefore, it is important that you memorise the facts that I have covered.

3.2.2 Electromagnetic Radiation and Quantum Phenomena

3.2.2.1 The Photoelectric Effect

Content

- Threshold frequency; photon explanation of threshold frequency.
- Work function ϕ, stopping potential.
- Photoelectric equation: $hf = \phi + E_{k(max)}$

Opportunities for Skills Development

- Demonstration of the photoelectric effect using a photocell or an electroscope with a zinc plate attachment and UV lamp.

What is the Photoelectric Effect?

It is where electrons are emitted from the surface of a metal when light shines at it. Formerly light was thought of as a wave, but various remarkable observations led scientists to believe that actually light behaves both as a wave and a particle, dependent on the situation. There are many reasons that in the photoelectric effect light cannot be a wave:

1. Electrons are emitted immediately after light shines on the metal. If light were a wave then there should be a lag before this happens, whilst the energy required to remove the electrons builds up.
2. Increasing the intensity of the light increased the number of photoelectrons, but not the maximum kinetic energy of these electrons. If light were a wave, then the maximum kinetic energy of the photoelectrons should increase as intensity is increased, however the number of photoelectrons should not be affected.
3. Red light will not cause electrons to be emitted no matter what the intensity is, if it were a wave then eventually electrons would be emitted from red light as the electrons gained more energy.

This led to the concepts I will move on to now, like threshold frequency, work function, stopping potential and others.

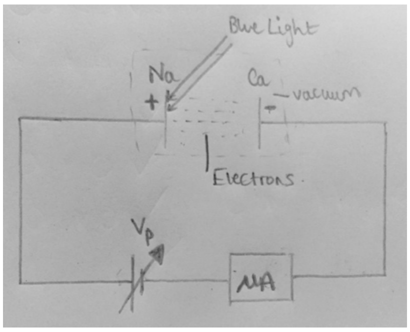
Threshold frequency

Threshold frequency (f_0) is the minimum frequency of a photon (incident light) required to eject photoelectrons from a metal surface. Photons each have a certain amount of energy which is equal to "hf", h being Planck's constant, and f being their frequency. The photon hits the metal at a certain frequency and if $f > f_0$ then threshold frequency is met. This amount of energy is just enough to eject them, however not give them any extra energy (kinetic) to travel further.

Work Function and Stopping Potential

Work function is the minimum energy of a photon (incident light) required to move an electron from within the metal to the surface of the metal (photoelectron emission). It is denoted as ϕ and is equal to the product of hf_0. It is a property of a material, and therefore is different for every material. If a photon comes in with twice the work function in energy, then the leftover energy will go to kinetic energy in moving it from the surface of the metal onwards.

If you have a circuit shown below whereby light is being shone onto a metal and photoelectrons are being released, the photoelectrons will be released with energy. This energy has a maximum and so if the distance between the positive and negative terminal is too far then photoelectrons will not reach the other side as none will have enough energy. Although if you move it closer so that you start to show a current as electrons reach the other side, then your circuit will be complete with a current. However if $V_p \neq 0$, then the photoelectrons travelling from the positive to the negative terminal will lose energy, as it will oppose their direction of travel. Therefore, the current will decease, and when current becomes 0, this can be called the stopping potential i.e. the potential difference (V) that causes the current to become 0, and ultimately stops photoelectrons from reaching the other side and completing the circuit. Therefore work is done on the electrons to stop them, this work done is equal to W=QV, here V is the stopping voltage, and Q is the charge, so in this case the charge on the electron. Thus you can work out the maximum kinetic energy of the electrons, as the stopping potential causes the electrons with maximum kinetic energy to lose all of their energy. To work out maximum kinetic energy you would substitute into the equation W=QV, this would be the charge on the electron multiplied by whatever stopping voltage you would have calculated, and this gives you the maximum K.E of the electrons.



You will not be required to recall the experimental determination of stopping potential, but it is useful to know in order to consolidate your understanding.

Photoelectric Equation

$hf = \phi + E_{k(max)}$ which can be rearranged to give $hf - \phi = E_{k(max)}$, thus another way of finding the maximum kinetic energy of the photoelectrons.

Main Factors Affecting the number of Photoelectrons Emitted:

1. The nature of the material i.e. the work function of the material.
2. The frequency of incident radiation.
3. The intensity of incident radiation

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'When monochromatic light is shone on a clean cadmium surface, electrons with a range of kinetic energies up to a maximum of 3.51 $x10^{-20}$ J are released. The *work function* of cadmium is 4.07 eV.'

'State what is meant by work function.'

- It is the minimum energy required to remove an electron from metal (surface).

'Explain why the emitted electrons have a range of kinetic energies up to a maximum value.'

- Photons have energy dependent on frequency/ the energy of photons is constant
- There is a one to one interaction between photons and electron
- Max KE = photon energy – work function
- More energy required to remove deeper electrons so they will be emitted with less kinetic energy

'Calculate the frequency of the light. Give your answer to an appropriate number of significant figures.'

- (Use of $hf=\phi+E_{k(max)}$)
- So $hf=\phi+E_{k(max)}$, thus f must equal $\phi+E_{k(max)}/h$
- $\phi = 4.07 \times 1.6 \times 10^{-19}$, $E_{k(max)} = 3.51 \times 10^{-20}$ and $h = 6.63 \times 10^{-34}$.

AQA Jan 2011 Unit 1

Question:

The photoelectric effect suggests that electromagnetic waves can exhibit particle - like behaviour. Explain what is meant by threshold frequency and why the existence of a threshold frequency supports the particle nature of electromagnetic waves.

The quality of your written communication will be assessed in this question.

Answer:

- Threshold frequency minimum frequency for emission of electrons
- If frequency below the threshold frequency, no emission even if intensity increased
- Because the energy of the photon is less than the work function
- Wave theory can not explain this as energy of wave increases with intensity
- Light travels as photons
- Photons have energy that depends on frequency
- If frequency is above threshold photon have enough energy
- Mention of lack of time delay

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Question:

State what is meant by the *photoelectric effect*.

Answer:

The emission of electrons from the surface of a metal when electromagnetic waves (of frequency greater than the threshold frequency) are incident on the metal

Question:

The photoelectric effect cannot be explained in terms of the wave-model of electromagnetic waves. Discuss how the new knowledge of the particulate nature of radiation was used by physicists to validate the photon model.

Answer:

The wave model cannot explain why there is a threshold frequency for metals.

The new model / photon model proposed one-to-one interaction between photons and electrons and this successfully explained why threshold frequency exists.

Any further one from:
Energy of photon (hf) must be greater than or equal to work function of metal.
The kinetic energy of emitted electrons was independent of the incident intensity.
Correct reference to $hf = \Phi + KE_{max}$

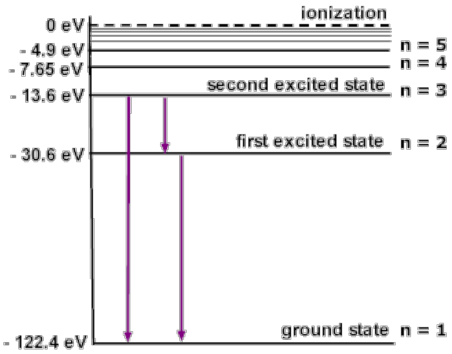
3.2.2.2 Collisions of Electrons with Atoms

Content

- Ionisation and excitation; understanding of ionisation and excitation in the fluorescent tube.
- The electron volt.
- Students will be expected to convert eV into J and vice versa.

Ionisation and Excitation, example in a Fluorescent Tube

To understand ionisation and excitation you must first understand energy levels and the role of electrons within this. Atoms are said to have discrete energy levels within them, energy levels that electrons can move up to, as shown below.



The first level is called the ground state, where all electrons will begin. They can then move up through the discrete energy levels if given the correct amount of energy, as the energy levels are specific and will not change. Therefore, outside high energy electrons passing through a gas will collide with orbital electrons and give them energy. If given the correct amount of energy, these electrons are then said to be excited so they will move up energy levels from ground state. However, to be ionised, the electron in ground state must be given enough energy to leave the atom, and move up past the highest energy level, not just move up one or two energy levels. The final key point is that when electrons fall back down the energy level to ground state again, or just to a lower energy, they will emit a photon. This photon will have energy E=hf, dependent on how much energy is lost when the electron falls. If the electron were to fall from energy level n=3 to n=1, it would lose a different discrete amount of energy in contrary to if it fell from level n=3 to ground state. Therefore photons of different energy would be emitted, so photons of different frequencies would be released, frequency of E/h = f by rearranging the equation.

If you apply this scenario to a fluorescent tube, it goes that within the glass of the narrow tube, there are two electrical connections on either side, allowing a current to be passed through. The tube also contains mercury vapor alongside an inert (unreactive) gas like argon or neon. A high voltage is then required to start the flow of current. Then high energy electrons will bombard orbital electrons, providing them with energy. This energy will excite orbital electrons, raising them from ground state to higher, discrete energy levels. After the electrons fall they will release photons of frequency E/h, with a mixture of fixed frequencies due to the different levels the electrons have fallen to and from. The frequency of the photons released is categorised as UV radiation. The inside of the tube is then coated with phosphorous material that emits visible light when **excited** with UV radiation and gives off visible light as the electrons de-excite and release slightly less energy. These lights are four to six times more efficient than incandescent bulbs and will not affect room temperature drastically, allowing a cool office environment to stay cool.

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Question:

‘State what is meant by the ionisation energy of hydrogen.’

Answer:

- Energy required to (completely) remove an electron from atom/hydrogen
- Ground state/lowest energy level

3.2.2.3 Energy Levels and Photon Emission

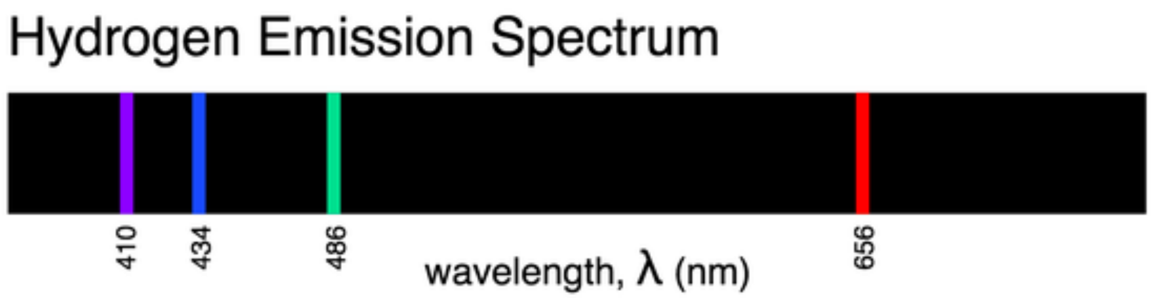
Content

- Line spectra (e.g. of atomic hydrogen) as evidence for transitions between discrete energy levels in atoms.
- $hf = E_2 - E_1$
- In questions, energy levels may be quoted in J or eV.

Opportunities for Skills Development

- Observation of line spectra using a diffraction grating.

Line Spectra



As you can see, the line spectra of hydrogen are shown above. This line spectra, and the colours shown correlate to the frequencies of light released equal to E/h when the photons fall from the different energy levels after excitation within the atom. So its clear there are few energy levels in hydrogen as very few colours on the visible light spectrum are visible.

The way you work out the frequency of the photons released is by subtracting the final energy level from the initial energy level. For example, if the electron falls from n=5 to n=3 there will be a drop in E energy, this energy will be equal to the energy of n=5 (E_1) subtracted from the energy on n=3 (E_2) so $E_2 - E_1$. This energy will give a discrete frequency by rearranging the equation to E/h=f.

They may give the values of the energy levels in eV or J, usually it will be in eV.

3.2.2.4 Wave-particle Duality

Content

- Students should know that electron diffraction suggests that particles possess wave properties and the photoelectric effect suggests that electromagnetic waves have a particulate nature.
- Details of particular methods of particle diffraction are not expected.
- de Broglie Wavelength $\lambda = h/mv$ where mv is the momentum.
- Students should be able to explain how and why the amount of diffraction changes when the momentum of the particle is changed.
- Appreciation of how knowledge and understanding of the nature of matter changes over time.
- Appreciation that such changes need to be evaluated through peer review and validated by the scientific community.

Opportunities for Skills Development

- Demonstration using an electron diffraction tube.
- Use prefixes when expressing wavelength values.

Electron Diffraction

Electron diffraction suggests that particles also possess wave properties, as a property of a wave is that it can diffract as particles cannot. So whereas the photoelectric effect shows that electromagnetic waves have particulate nature, electron diffraction shows the opposite. This ultimately shows wave-particle duality.

de Broglie Wavelength

de Broglie wavelength is used to determine wavelength, and is found using $\lambda = h/mv$. "h" is a constant so will never change, therefore the effect of changes in momentum heavily impacts the wavelength. If you have a momentum M, then h/M will be the wavelength. If this momentum is doubled you will get h/2M, so wavelength will be halved as h is now being divided by a larger number. Whereas if the momentum is halved to get M/2, then h/M/2 will give you double the wavelength. We know that longer wavelengths will diffract more than smaller wavelengths, so decreasing momentum will cause increased diffraction.

Appreciation of how knowledge and understanding of the nature of matter changes over time.

Appreciation that such changes need to be evaluated through peer review and validated by the scientific community.

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'In order to explain the photoelectric effect, the wave model of electromagnetic radiation was replaced by the photon model. Explain what must happen in order for an existing scientific theory to be modified or replaced with a new theory.'

- Theory makes predictions that are then tested and are repeatable/checked by other scientists/peer reviewed experimentally

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'State the steps taken by the scientific community for the value of a quantity to be accepted (line 13).'

- The **method** and **values** are published
- Other scientists repeat the experiment using the **same method**