**Leaving Cert Physics Long Questions 2018 - 2002**

***15. Particle Physics***

***Please remember to photocopy 4 pages onto one sheet by going A3→A4 and using back to back on the photocopier***

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# Key to answering particle physics maths questions

Maths questions in this topic are all about energy conversions

The energy can take one of four forms.

1. It can be *potential energy*: **W = QV**

(Q is charge, V is potential difference)

Example: Linear accelerators

1. It can be *kinetic energy*: **E = ½ mv2**  
   (m is mass, v is velocity)

Example: Proton-proton collisions

1. It can be in the form of *electromagnetic radiation* where **E = hf**   
   (f is frequency, h is Planck’s constant)

Example: Pair production

1. It can be in the form of *mass*, in which case the energy equivalent is **E = mc2**

(m is mass, c is the speed of light)

Example: Large Hadron Collider, Pair annihilation

The context will determine which of the above equations you will need

**Notes**

1. Make sure you can convert from electron-Volts (eV) to Joules (J) and vice-versa

(1eV =1.6 x 10–19 Joules)

1. Be comfortable dealing with very large numbers and very small numbers on your calculator.
2. **Be comfortable using the log-table to find all relevant information, particularly the mass of the particles.  
   In particular note that page 47 and page 83 are the most used pages.  
   Note also that on page 83, masses of nuclei are given in terms of the atomic mass unit (*u*).   
   You then need to go to page 47 to find the mass of one atomic mass unit.**

# Energy conversions – all you need to know

**Linear Accelerator**

*potential energy* → *kinetic energy* ***QV → ½ mv2***

**Cockroft and Walton experiment**

Some of the mass beforehand disappears and is converted into kinetic energy of the new particles

*mass → kinetic energy*

** +  →  + K.E.**

**mc2 → K.E**

**Proton-Proton Collisions**

The kinetic energy of the protons just before the collision is converted into the mass of the new particles which were created just after the collision

*kinetic energy → mass*

***+ + kinetic energy = + + additional particles***

**{+ *K.E. of the newly created particles*}**

**K.E → mc2 {+ K.E.}**

**Pair Production**

Energy in the form of electromagnetic radiation (associated with gamma radiation) is converted into mass.

***→ e- + e+ {+ K.E. of the newly created particles}***

**hf → 2c2**

**Pair Annihilation**

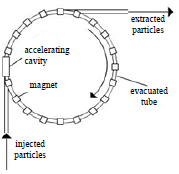
Mass is converted into energy in the form of electromagnetic radiation.

**2c2 → 2hf**

# Particle accelerators (including Cockcroft and Walton experiment)

**2013 Question 10 (a)**

In 1932 J.D. Cockroft and E.T.S. Walton accelerated protons to energies of up to 700 keV and used them to bombard a lithium target. They observed the production of alpha-particles from the collisions between the accelerated protons and the lithium nuclei.

1. How did Cockroft and Walton accelerate the protons?
2. How did they detect the alpha-particles?
3. Write the nuclear equation for the reaction that occurred and indicate the historical significance of their observation.
4. Calculate the speed of a proton that has a kinetic energy of 700 keV.

Many modern particle accelerators, such as the Large Hadron Collider (LHC) in CERN, have a circular design.

The diagram shows a simplified design of a circular accelerator.

1. Why is the tube evacuated?
2. What is the purpose of accelerating the particles to high velocities?
3. What is the purpose of the magnets?
4. Give an advantage of a circular accelerator over a linear accelerator.
5. Can an accelerator of this design be used to accelerate neutrons? Explain your answer.

**2007 Question 10 (a)**

Read the following passage and answer the accompanying questions.

Ernest Walton was one of the legendary pioneers who made 1932 the annus mirabilis of experimental nuclear physics. In that year James Chadwick discovered the neutron; Carl Anderson discovered the positron; Fermi articulated his theory of radioactive decay; and Ernest Walton and John Cockcroft split the nucleus by artificial means. In their pioneering experiment Cockcroft and Walton bombarded lithium nuclei with high-energy protons linearly accelerated across a high potential difference (c. 700 kV). The subsequent disintegration of each lithium nucleus yielded two helium nuclei and energy. Their work gained them the Nobel Prize in 1951.

(Adapted from “Ernest Thomas Sinton Walton 1903 –1995 The Irish Scientist” McBrierty; 2003)

1. Draw a labelled diagram to show how Cockcroft and Walton accelerated the protons.
2. What is the velocity of a proton when it is accelerated from rest through a potential difference of 700 kV?
3. Write a nuclear equation to represent the disintegration of a lithium nucleus when bombarded with a proton.
4. Calculate the energy released in this disintegration.
5. Compare the properties of an electron with that of a positron.
6. What happens when an electron meets a positron?
7. In beta decay it appeared that momentum was not conserved. How did Fermi’s theory of radioactive decay resolve this?

charge on electron = 1.6022 × 10–19 C; mass of proton = 1.6726 × 10–27 kg;

speed of light = 2.9979 × 108 m s–1

mass of lithium nucleus = 1.1646 × 10–26 kg; mass of helium nucleus = 6.6443 × 10–27 kg;

**2017 Question 12 (d)**

In the Cockcroft and Walton experiment, accelerated protons collided with lithium nuclei. In each collision a proton collided with a lithium nucleus to produce two alpha-particles, as shown in this commemorative coin.

1. Explain how the protons were produced.
2. Explain how the protons were accelerated.
3. Explain how the alpha-particles were detected.
4. Write the nuclear equation for this reaction.
5. For this reaction, calculate the loss in mass and hence the energy released (in MeV).
6. Explain the historical significance of this experiment.

**2002 Question 10 (a)**

1. Name the four fundamental forces of nature.
2. Which force is responsible for binding the nucleus of an atom?
3. Give two properties of this force.
4. In 1932, Cockcroft and Walton carried out an experiment in which they used high-energy protons to split a lithium nucleus. Outline this experiment.
5. When a lithium nucleus () is bombarded with a high-energy proton, two α-particles are produced.

Write a nuclear equation to represent this reaction.

1. Calculate the energy released in this reaction.

mass of proton = 1.6730 × 10-27 kg; mass of lithium nucleus = 1.1646 × 10-26 kg;   
mass of α-particle = 6.6443 × 10-27 kg; speed of light, c = 3.00 × 108 m s-1.

**2005 Question 11 (a)**

Read the following passage and answer the accompanying questions.

Ernest Rutherford made the following point:

If the particles that come out naturally from radium are no longer adequate for my purposes in the laboratory, then maybe the time had come to look at ways of producing streams of fast particles artificially.

High voltages should be employed for the task.

A machine producing millions of alpha particles or protons would be required. These projectiles would be released close to a high voltage and would reel away at high speed. It would be an artificial particle accelerator. Potentially such apparatus might allow physicists to break up all atomic nuclei at will.

(Adapted from “The Fly in the Cathedral” Brian Cathcart; 2004)

1. What is the structure of an alpha particle?
2. Rutherford had bombarded gold foil with alpha particles. What conclusion did he form about the structure of the atom?
3. High voltages can be used to accelerate alpha particles and protons but not neutrons.Explain why.
4. Cockcroft and Walton, under the guidance of Rutherford, used a linear particle accelerator to artificially split a lithium nucleus by bombarding it with high-speed protons. Copy and complete the following nuclear equation for this reaction.



1. Circular particle accelerators were later developed. Give an advantage of circular accelerators over linear accelerators.
2. In an accelerator, two high-speed protons collide and a series of new particles are produced, in addition to the two original protons.

Explain why new particles are produced.

1. A huge collection of new particles was produced using circular accelerators. The quark model was proposed to put order on the new particles.

List the six flavours of quark.

1. Give the quark composition of the proton.

(Refer to Mathematics Tables, p. 44.)

# Maths questions involving protons colliding in a particle accelerator

**2009 Question 10** **(a)**

In 1932 Cockcroft and Walton succeeded in splitting lithium nuclei by bombarding them with artificially accelerated protons using a linear accelerator.

Each time a lithium nucleus was split a pair of alpha particles was produced.

1. How were the protons accelerated?
2. How were the alpha particles detected?
3. Write a nuclear equation to represent the splitting of a lithium nucleus by a proton.
4. Calculate the energy released in this reaction.
5. Most of the accelerated protons did not split a lithium nucleus. Explain why.

Cockcroft and Walton’s apparatus is now displayed at CERN in Switzerland, where very high energy protons are used in the Large Hadron Collider.

In the Large Hadron Collider, two beams of protons are accelerated to high energies in a circular accelerator. The two beams of protons then collide producing new particles. Each proton in the beams has a kinetic energy of 2.0 GeV.

1. Explain why new particles are formed.
2. What is the maximum net mass of the new particles created per collision?
3. What is the advantage of using circular particle accelerators in particle physics?

(mass of alpha particle = 6.6447 × 10–27 kg; mass of proton = 1.6726 × 10–27 kg;

mass of lithium nucleus = 1.1646 × 10–26 kg; speed of light = 2.9979 × 108 m s–1;

charge on electron = 1.6022 × 10–19 C)

**2011 Question 10** **(*a*)**

1. List three quantities that are conserved in nuclear reactions.
2. Write an equation for a nucleus undergoing beta-decay.
3. In initial observations of beta-decay, not all three quantities appear to be conserved.

What was the solution to this contradiction?

1. List the fundamental forces of nature in increasing order of their strength.
2. Which fundamental force of nature is involved in beta-decay?
3. In the Large Hadron Collider, two protons with the same energy and travelling in opposite directions collide. Two protons and two charged pi mesons are produced in the collision.

Why are new particles produced in the collision?

1. Write an equation to represent the collision.
2. Show that the kinetic energy of each incident proton must be at least 140 MeV for the collision to occur.

**2008 Question 10 (a)**

Baryons and mesons are made up of quarks and experience the four fundamental forces of nature.

1. List the four fundamental forces and state the range of each one.
2. Name the three positively charged quarks.
3. What is the difference in the quark composition of a baryon and a meson?
4. What is the quark composition of the proton?
5. In a circular accelerator, two protons, each with a kinetic energy of 1 GeV, travelling in opposite directions, collide. After the collision two protons and three pions are emitted.

What is the net charge of the three pions? Justify your answer.

1. Calculate the combined kinetic energy of the particles after the collision
2. Calculate the maximum number of pions that could have been created during the collision.

(charge on electron = 1.6022 × 10–19 C; mass of proton = 1.6726 × 10–27 kg;

mass of pion = 2.4842 × 10–28 kg; speed of light = 2.9979 × 108 m s–1)

# Pair annihilation

**2016 Question 12 (d)**

*{this is the first time that Particle Physics did not come up as a full question. Pick your own adjective to describe the guy(s) who put that paper together. And yes it had to be a man.}*

1. The pair annihilation of an electron and a positron has been investigated for many years at CERN in Switzerland. Two gamma-ray photons are produced during this annihilation.  
   What is a positron?
2. Why are photons always produced in pairs during pair annihilation?
3. Write an equation for this annihilation.
4. Calculate the frequency of the gamma-radiation produced in this annihilation.
5. The pair annihilation of a proton and an anti-proton is now being investigated at CERN.

Compare the energy produced in these two annihilations.

Explain your answer.

**2014 Question 11** **(*a*)**

Read the following passage and answer the accompanying questions.

Cyclotrons and PET Scanners

Positron emission tomography (PET) scanners are designed to detect the pair of photons generated from the annihilation reaction between a positron and an electron.

A carbon–11 nucleus, which has a half-life of twenty minutes, decays with the emission of a positron. The positron travels only a short distance before colliding with an electron in the surrounding matter. Pair annihilation occurs. The emitted photons travel in opposite directions.

Cyclotrons are located in the same hospital as the PET scanners and are used to manufacture radioactive nuclei. Cyclotrons are circular devices in which charged particles are accelerated in a spiral path within a vacuum. The particles are accelerated by a rapidly alternating voltage and acquire high kinetic energies. They spiral outwards under the influence of the magnetic field until they have sufficent velocity and are deflected into a target producing radioactive nuclei, including carbon–11.

(Adapted from “*Essentials of Nuclear Medicine Physics*”;

Powsner & Powsner; 1998)

* 1. Electrons are leptons.   
     List the three fundamental forces that electrons experience in increasing order of strength.
  2. Write an equation to represent the pair annihilation described in the text.
  3. Calculate the frequency of each photon produced in this pair annihilation.
  4. Why do the photons produced in pair annihilation travel in opposite directions?
  5. Write a nuclear equation to represent the decay of carbon–11.
  6. What is the value of the decay constant of carbon–11?
  7. Explain why the carbon–11 nuclei used in the PET scanner must be produced in a cyclotron in, or close to, the same hospital as the scanner.
  8. Give an expression for the momentum of a particle in the cyclotron in terms of the magnetic flux density of the field, the charge on the particle and the radius of its circular path at any instant.

**2012 Question 10** **(a)**

1. What is a positron?
2. When a positron and an electron meet two photons are produced.  
   Write an equation to represent this interaction.
3. Why are photons produced in this interaction?
4. Explain why two photons are produced.
5. Calculate the minimum frequency of the photons produced.
6. Explain why the photons produced usually have a greater frequency than your calculated minimum frequency value.
7. Why must two protons travel at high speeds so as to collide with each other?
8. How are charged particles given high speeds?
9. Explain why two positrons cannot annihilate each other in a collision.

**2006 Question 10 (a)**

During a nuclear interaction an antiproton collides with a proton. Pair annihilation takes place and two gamma ray photons of the same frequency are produced.

1. What is a photon?
2. Calculate the frequency of a photon produced during the interaction.
3. Why are two photons produced?
4. Describe the motion of the photons after the interaction.
5. How is charge conserved during this interaction?
6. After the annihilation, pairs of negative and positive pions are produced. Explain why.
7. Pions are mesons that consist of up and down quarks and their antiquarks.

Give the quark composition of (i) a positive pion, (ii) a negative pion.

1. List the fundamental forces of nature that pions experience.
2. A neutral pion is unstable with a decay constant of 2.5 × 1012 s–1. What is the half-life of a neutral pion?

(mass of proton= 1.673 × 10–27 kg; Planck constant = 6.626 × 10–34 J s; speed of light = 2.998 × 108 m s–1 )

**2018 Question 10 (a)** 

Momentum, energy and charge are conserved in all nuclear reactions.

In beta‐decay an unstable nucleus emits an electron.

In the early 20th century it was found that momentum and energy did not appear to be conserved during beta‐decay. To solve this apparent problem, Wolfgang Pauli predicted the existence of an unknown particle, about which he said:

*I have done a terrible thing. I have postulated a particle that cannot be detected.*

1. Name the particle which Pauli predicted and explain how it solved the problem.
2. Write a nuclear equation for beta‐decay.
3. Why did Pauli think that the particle could not be detected?

The conservation laws also apply to pair annihilation.

Pair annihilation can be described using the following equation for an electron and a positron at rest.



1. Why are two gamma‐ray photons produced?
2. Explain how charge is conserved in the annihilation.
3. Calculate the maximum frequency of each emitted photon.
4. Electrons are negatively charged leptons. List the two other negatively charged leptons.
5. List the three forces that these leptons can experience, in decreasing order of strength.

# Pair production

**2010 Question 10 (a)**

1. What is anti-matter?
2. An anti-matter particle was first discovered during the study of cosmic rays in 1932.

Name the anti-particle and give its symbol.

1. What happens when a particle meets its anti-particle?
2. What is meant by pair production?
3. A photon of frequency 3.6 × 1020 Hz causes pair production.

Calculate the kinetic energy of one of the particles produced, each of which has a rest mass of 9.1×10–31 kg.

1. A member of a meson family consists of two particles. Each particle is composed of up and down quarks and their anti-particles.

Construct the possible combinations. Deduce the charge of each combination and identify each combination.

1. What famous Irish writer first thought up the name ‘quark’?

**2003 Question 10 (a)**

1. Leptons, baryons and mesons belong to the “particle zoo”.

Give (i) an example, (ii) a property, of each of these particles.

1. The following reaction represents pair production.

γ → e+ + e–

Calculate the minimum frequency of the γ-ray photon required for this reaction to occur.

1. What is the effect on the products of the reaction if the frequency of the γ-ray photon exceeds the minimum value?
2. The reverse of the above reaction is known as pair annihilation.

Write a reaction that represents pair annihilation.

1. Explain how the principle of conservation of charge and the principle of conservation of momentum apply in pair annihilation.

mass of electron = 9.1 × 10–31 kg; speed of light, *c* = 3.0 × 108 m s–1 ; Planck constant, *h* = 6.6 × 10–34 J s

# Neutrinos

**2015 Question 10 (a)**

There are about a trillion neutrinos from the Sun passing through your hand every second.

Neutrinos are fundamental particles and are members of the lepton family.

Leptons are not subject to the strong nuclear force.

1. What is the principal force that neutrinos experience?
2. Electrons are also members of the lepton family. Name two other leptons.
3. Name one fundamental particle that is subject to the strong nuclear force.
4. Pauli proposed that a neutrino is emitted during beta-decay.

Why did he make this proposal?

1. During beta-decay, a neutron decays with the emission of a proton, an electron and a neutrino.  
   Write a nuclear equation to represent beta-decay.
2. Calculate the energy released, in MeV, during beta-decay.
3. An electron can be detected in a cloud chamber.   
   However it is much more difficult to detect a neutrino. Explain why.
4. In a cloud chamber an electron travels perpendicular to the direction of a magnetic field of flux density 90 mT and it follows a circular path.   
   Calculate the radius of the circle when the electron has a speed of 1.45 × 108 m s–1.
5. Describe the path of a neutrino in the same magnetic field.

**2004 Question 10 (a)**

1. Beta decay is associated with the weak nuclear force.

List two other fundamental forces of nature and give one property of each force.

1. In beta decay, a neutron decays into a proton with the emission of an electron.

Write a nuclear equation for this decay. Calculate the energy released during the decay of a neutron.

1. Momentum and energy do not appear to be conserved in beta decay. Explain how the existence of the neutrino, which was first named by Enrico Fermi, resolved this.

During the late 1930s, Fermi continued to work on the nucleus.

His work led to the creation of the first nuclear fission reactor in Chicago during 1942.

The reactor consisted of a ‘pile’ of graphite moderator, uranium fuel with cadmium control rods.

1. What is nuclear fission?
2. What is the function of the moderator in the reactor?
3. How did the cadmium rods control the rate of fission?

mass of neutron = 1.6749 × 10–27 kg; mass of proton = 1.6726 × 10–27 kg;

mass of electron = 9.1094 × 10–31 kg; speed of light = 2.9979 × 108 m s–1

# Solutions

**2018 Question 10 (a)**

1. **Name the particle which Pauli predicted and explain how it solved the problem.**The neutrino; it had the missing energy and momentum
2. **Write a nuclear equation for beta‐decay.**
3. **Why did Pauli think that the particle could not be detected?**   
   It had no charge and very little mass.
4. **Why are two gamma‐ray photons produced?**To conserve momentum
5. **Explain how charge is conserved in the annihilation.**  
   Net charge beforehand = 0 (since the particle and antiparticle have equal and opposite charges)

Photons have no charge so charge afterwards = 0.

1. **Calculate the maximum frequency** **of each emitted photon.**  
   Mass of electron = 9.1093826 × 10-31 kg

Energy ‘released’ when one electron is annihilated = mc2

We only need to look at one electron because two electrons are annihilated to produce two photons, so it’s as if one electron is responsible for producing one photon.

E = (9.1093826 × 10-31)(3 × 108)2

E = 8.198444 × 10-14 J

This energy now goes on to create a photon

Energy associated with a photon = hf

*f* = 1.24 × 1020 Hz

1. **Electrons are negatively charged leptons. List the two other negatively charged leptons.**  
   muon, tau
2. **List the three forces that these leptons can experience, in decreasing order of strength.**   
   electromagnetic, weak, gravitational

**2017 Question 12 (d)**

1. **Explain how the protons were produced.**ionisation / discharge tube
2. **Explain how the protons were accelerated.**  
   high voltage
3. **Explain how the alpha-particles were detected.**

flashes / zinc sulphide / screen

1. **Write the nuclear equation for this reaction.**   
   ** +  →  + K.E.**

For this reaction, calculate the loss in mass and hence the energy released (in MeV).   
Mass beforehand (mass of reactants) = 1.1646 × 10-26 + 1.6726 × 10-27 = 1.33186 × 10-26 kg

Mass afterwards (mass of products) = 2(6.6443 × 10-27) = 1.32886 × 10-26 kg

Loss in mass = 1.33186 × 10-26 kg - 1.32886 × 10-26 kg = 3.00 × 10-29 kg

*E* = *mc2* or = (3.00 × 10-29)(9 × 1016) = 2.7 × 10-12 J

Converting to eV: 1.6 × 10-19 J = 1 eV

2.7 × 10-12 J = eV = 17.35 × 106 eV = 17.35 MeV

1. **Explain the historical significance of this experiment.**

Verified 𝑬=𝒎𝒄𝟐/ first transmutation by an artificially accelerated particle / important step in development of the particle accelerator / Nobel prize

**2016 Question 12 (d)**

1. **What is a positron?**

Positively charged electron // anti-electron

1. **Why are photons always produced in pairs during pair annihilation?**

To conserve momentum

1. **Write an equation for this annihilation.**
2. **Calculate the frequency of the gamma-radiation produced in this annihilation.**

Mass of electron = 9.1093826 × 10-31 kg

Energy ‘released’ when one electron is annihilated = mc2

We only need to look at one electron because two electrons are annihilated to produce two photons, so it’s as if one electron is responsible for producing one photon.

E = (9.1093826 × 10-31)(3 × 108)2

E = 8.198444 × 10-14 J

This energy now goes on to create a photon

Energy associated with a photon = hf

f = 1.237 × 1020 Hz

1. **Compare the energy produced in these two annihilations.**

**Explain your answer.**

Energy from proton annihilation is greater because a proton’s mass is greater

**2015 Question 10 (a)**

1. **What is the principal force that neutrinos experience?** Weak (nuclear force)
2. **Name two other leptons.** Muon, tau, positron
3. **Name one fundamental particle that is subject to the strong nuclear force.** Quark
4. **Why did he make this proposal?** Momentum/energy not conserved
5. **Write a nuclear equation to represent beta-decay.**
6. **Calculate the energy released, in MeV, during beta-decay.**

Page 46, 47 and 48 of log tables to get values for the mass of the particles.

Mass of neutron: 1.674 927 28 × 10-27 kg Mass of proton: 1.672 621 71 × 10-27 kg

Mass of electron: 9.109 3826 × 10-31 kg

Mass of neutrino: see page 48 of log tables; the mass of the neutrino is given relative to the mass of an electron. Mass of neutrino = (4.305 × 10-6)(9.109 3826 × 10-31) = 3.921589209 × 10-36 kg

**Mass before = mass of neutron= 1.674 927 28 × 10–27 kg**

Mass after = mass of proton + mass of electron + mass of neutrino

= 1.672 621 71 × 10-27 kg + 9.109 3826 × 10-31 kg + 3.921589209 × 10-36 kg

**Total mass after = 1.673532652 × 10-27 kg**

Loss in mass = total mass beforehand – total mass afterwards

= (**1.674 927 28 × 10–27 kg**) – (**1.673532652 × 10-27 kg**)

Loss in mass = 1.395 × 10–30 kg

To calculate the energy associated with this mass we need to use E = mc2   
E = (1.395 × 10–30)(2.997 924 58)2 E = 1.25 × 10-13 J

Now we need to convert from Joules to eV

1 eV = 1.602 176 53 × 10-19 J {page 46 of log tables}

So we need to divide 1.25 × 10-13 by 1.602 176 53 × 10-19 E = 780188 eV

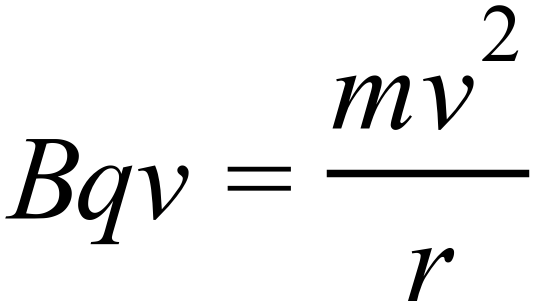
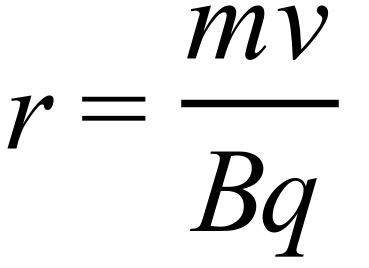
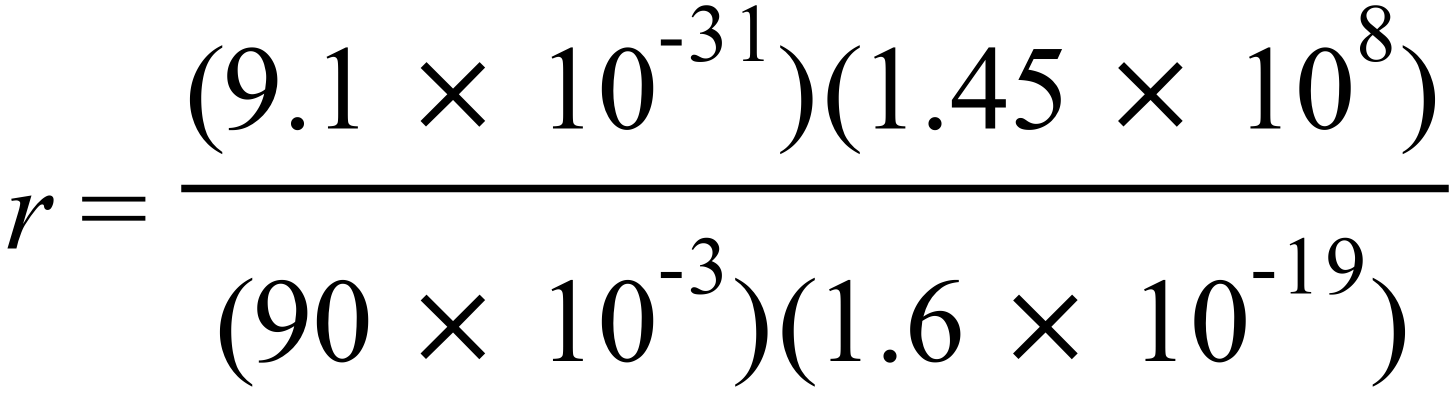
Now divide by 1×106 to convert to MeV {M = mega = 106} E = 0.78 MeV

1. **However it is much more difficult to detect a neutrino. Explain why.**The neutrino has no charge and only a very small mass.
2. **Calculate the radius of the circle when the electron has a speed of 1.45 × 108 m s–1.**

The force experience by a charged particle in a magnetic field is given by the equation F = *Bqv*.

The force experience by a particle moving in a circle is given by the equation F = *mv*2/*r*

Equating both expressions:

   r = 9.16 × 10–3 m

1. **Describe the path of a neutrino in the same magnetic field.**No deviation

**2014 Question 11** **(*a*)**

1. **List the three fundamental forces that electrons experience in increasing order of strength.**  
   gravitational, weak (nuclear) and electromagnetic
2. **Write an equation to represent the pair annihilation described in the text.**

e− + e+ → 2hf

OR

1. **Calculate the frequency of each photon produced in this pair annihilation.**

Mass of electron = 9.1093826 × 10-31 kg

Energy ‘released’ when one electron is annihilated = mc2

We only need to look at one electron because two electrons are annihilated to produce two photons, so it’s as if one electron is responsible for producing one photon.

E = (9.1093826 × 10-31)(3 × 108)2

E = 8.198444 × 10-14 J

This energy now goes on to create a photon

Energy associated with a photon = *hf*

*f* = 1.237 × 1020 Hz

1. **Why do the photons produced in pair annihilation travel in opposite directions?**momentum is conserved
2. A carbon–11 nucleus, which has a half-life of twenty minutes, decays with the emission of a positron. **Write a nuclear equation to represent the decay of carbon–11.***{This is the first time we have come across what is known as beta-positive decay, where instead of a neutron decaying into a proton plus electron (beta-minus decay), we have a proton decaying into a neutron plus a positron. Physicists must have done some serious head-scratching the day that baby was born. Technically, there was nothing to say that this was on the syllabus. Then again, technically, there was nothing to say it wasn’t.}*
3. **What is the value of the decay constant of carbon–11?**

T1/2 = λ = Half-life is 20 minutes = (20)(60) = 1200 seconds

λ = λ = 0.000578 s−1

1. **Explain why . . .**  
   Because of their short half-life - too many would have decayed before they could be used.
2. **Give an expression . . .** *The word ‘radius’ is the clue that tells us we’re talking about a centripetal force, the term ‘magnetic flux density’ is the clue that tells us that we’re talking about a magnetic force.*

*Equate the expression for both and rearrange so that we get mv (momentum) on one side:*

Centripetal force = magnetic force

Cancel one *v* on both sides and multiply both sides by *r* to get rid of the r on the left hand side.  
⇒ m*v* = *Bqr*

**2013 Question 10** **(*a*)**

1. **How did Cockroft and Walton accelerate the protons?**  
   High voltage / large electric field
2. **How did they detect the alpha-particles**?   
   When the alpha particles hit a zinc sulfide screen it resulted in flashes of light
3. **Write the nuclear equation for the reaction that occurred.**

** +  →  + K.E.**

1. **Indicate the historical significance of their observation.**

It was the 1st experimental verification of *E = mc2* / first artificial splitting of the nucleus (atom) /   
first transmutation using artificially accelerated particles

1. **Calculate the speed of a proton that has a kinetic energy of 700 keV.**   
   The kinetic energy is 700 keV, so we need to convert this to Joules.

1eV =1.6 x 10–19 Joules

700 keV = (700 x 103)(1.6 x 10–19) Joules

Kinetic energy = 1.12 × 10–13 J

Now we use Ekinetic = ½mv2

1.12 × 10–13 = ½ mv2

Mass of proton = 1.6730 × 10-27 kg

*v =* 1.16 × 107 m s−1

1. **Why is the tube evacuated?**   
   So that particles do not collide with gas particles
2. **What is the purpose of accelerating the particles to high velocities?**   
   To overcome repulsive forces // to create new matter
3. **What is the purpose of the magnets?**   
   To contain the particles (in a circular path)
4. **Give an advantage of a circular accelerator over a linear accelerator.**  
   Takes up less space // particles can achieve greater energy / speed
5. **Can an accelerator of this design be used to accelerate neutrons? Explain your answer.**  
   No  
   Neutrons have no charge and are therefore not affected by electric / magnetic fields

**2012 Question 10** **(*a*)**

1. **What is a positron?**

A positron is an electron with a positive charge.

1. **When a positron and an electron meet two photons are produced.**

**Write an equation to represent this interaction.**

OR

1. **Why are photons produced in this interaction?**

The mass of the electron and positron gets converted into energy

1. **Explain why two photons are produced.**

To conserve momentum.

1. **Calculate the minimum frequency of the photons produced.**

*Two electrons ‘disappear’ and two photons are created, so we can assume that the each electron ‘is converted to’ a photon.*

Mass of electron = 9.1093826 × 10-31 kg

The energy associated with an electron is given by *E = mc2*

*E* = (9.1093826 × 10-31)(3 × 108)2

*E* = 8.198444 × 10-14 J

This now becomes the energy of the photon:*E = hf*

*f* = 1.237 × 1020 Hz

1. **Explain why the photons produced usually have a greater frequency than your calculated minimum frequency value.**

In addition to rest mass the colliding particles have kinetic energy.

1. **Why must two positrons travel at high speeds so as to collide with each other?**

To overcome the force of repulsion

1. **How are charged particles given high speeds?**

Particle accelerators / linear accelerator / cyclotron /synchrotron/magnetic fields/electric fields

1. **Explain why two positrons cannot annihilate each other in a collision.**

This would involve a conflict with conservation of charge.

**2011 Question 10** **(*a*)**

1. **List three quantities that are conserved in nuclear reactions.**

Momentum, charge, mass-energy

1. **Write an equation for a nucleus undergoing beta-decay.**
2. **In initial observations of beta-decay, not all three quantities appear to be conserved.**

**What was the solution to this contradiction?**

The discovery of the neutrino which accounted for the missing momentum.

1. **List the fundamental forces of nature in increasing order of their strength.**

gravitational < weak (nuclear) < electromagnetic < (strong) nuclear

1. **Which fundamental force of nature is involved in beta-decay?**

The weak force.

1. **Why are new particles produced in the collision?**

The kinetic energy of the protons is converted into mass.

1. **Write an equation to represent the collision.**

p + p + KE p + p + + + π- + KE

1. **Show that the kinetic energy of each incident proton must be at least 140 MeV for the collision to occur.**

*We need to find out how much energy is required to produce {just} two pions {with no kinetic energy}.*

*So we will be using E = 2mπc2 where mπ represents the mass of one pion.*

*But we don’t have a value for the mass of a pion, just it’s mass relative to the mass of an electron.*

Mass of π+ = (273)(me) = 273(9.109×10-31 kg) = 2.4869×10-28 kg

E = 2mπc2

E = 2(2.4869×10-28)(3×108)2 = 44.76 ×10-12 J

We now need to convert this to eV. 1 eV = 1.602 ×10-19 Joules, so we need to divide the our number in Joules by 1.602 ×10-19 to get the equivalent value in eV.

This is the *total* kinetic energy associated with two protons, so the kinetic energy of each proton must be 140 MeV.

**2010 Question 10 (a)**

1. **What is anti-matter?**

Antimatter is material/matter/particles that has the same mass as another particle but opposite charge.

1. **Name the anti-particle and give its symbol.**

positron / anti-electron

1. **What happens when a particle meets its anti-particle?**

Pair annihilation occurs and the mass gets converted to energy.

1. **What is meant by pair production?**

Pair production involves the production of a particle and its antiparticle from a gamma ray photon.

1. **Calculate the kinetic energy of one of the particles produced, each of which has a rest mass of 9.1 × 10–31 kg.**

Energy of incident photon = energy required to create 2 particles + kinetic energy of particles

Energy of incident photon = *hf* E = (6.6 × 10-34)( 3.6 × 1020) = 2.376 × 10-13 J

Energy required to produce the *two* particles = 2[mc2]

E = 2(9.1 × 10-31)(3.0 × 108)2 = 1.638 × 10-13 J

Energy of incident photon = energy required to create 2 particles + kinetic energy of particles

2.376 × 10-13 J = 1.638 × 10-13 J + kinetic energy

Extra energy available for kinetic energy = (2.376 × 10-13) – (1.638 × 10-13) = 7.38 × 10-14

Kinetic energy *per particle* is half of this = 3.69 × 10-14 Joules

1. **Construct the possible combinations.**

**Deduce the charge of each combination and identify each combination.**

|  |  |  |  |
| --- | --- | --- | --- |
| **composition** | | **charge** | **name** |
| u |  | 0 | Pi-neutrino |
| u |  | +1 | Pi-plus |
| d |  | -1 | Pi-minus |
| d |  | 0 | Pi-neutrino |
|  |  |  |  |

1. **What famous Irish writer first thought up the name ‘quark’?**

James Joyce

**2009 Question 10** **(a)**

1. **How were the protons accelerated?**

They were accelerated by the very large potential difference which existed between the top and the bottom

1. **How were the alpha particles detected?**

They collide with a zinc sulphide screen, where they cause a flash and get detected by microscopes.

1. **Write a nuclear equation to represent the splitting of a lithium nucleus by a proton.**

** +  →**  + K.E.

1. **Calculate the energy released in this reaction.**

Loss in mass:

Mass before = mass of proton + mass of lithium nucleus

= (1.6726 × 10–27) + (1.1646 × 10–26)

= 1.33186 × 10-26 kg

Mass after = mass of two alpha particles = 2 × (6.6447 × 10–27) = 1.32894 × 10-26 kg

Loss in mass = (1.33186 × 10-26) – (1.32894 × 10-26) = 2.92 × 10-29 kg

E = mc2 = (2.92 × 10-29) (2.9979 × 108)2 = 2.6 × 10-12 J

1. **Most of the accelerated protons did not split a lithium nucleus. Explain why.**

The atom is mostly empty space so the protons passed straight through.

1. **Explain why new particles are formed.**

When the protons collide into each other they lose their kinetic energy and it is this energy which gets converted into mass to form the new particles.

1. **What is the maximum net mass of the new particles created per collision?**

The maximum that can be created would occur if all of the kinetic energy was converted into mass.

Total energy = 4 GeV

G = Giga = × 109

1 eV = 1.6 × 10-19 Joules

4 GeV = (4 × 109) (1.6 × 10-19) = 6.4× 10-10 Joules

E = mc2   m = 7.121 × 10-27 kg

1. **What is the advantage of using circular particle accelerators in particle physics?**

You can achieve greater (particle) speeds with a circular accelerator / They take up less space

**2008 Question 10 (a)**

1. **List the four fundamental forces and state the range of each one.**

Strong (short range), Weak (short range), Gravitational (infinite range), Electromagnetic (infinite range).  
We should really be more specific here in relation to the range of the Strong and Weak forces and say that their range is of the order of the diameter of the nucleus of an atom.

1. **Name the three positively charged quarks.**

Up, top, charm.

1. **What is the difference in the quark composition of a baryon and a meson?**

Baryon: three quarks

Meson: one quark and one antiquark

1. **What is the quark composition of the proton?**

Up, up, down

1. **What is the net charge of the three pions? Justify your answer.**

The total charge beforehand was +2 (due to the two protons).

Therefore the total charge afterwards must be +2 (due to conservation of charge).

But there are also 2 protons afterwards, so they account for the +2 by themselves.

So the net charge (or all other particles added together) must therefore be zero.

1. **Calculate the combined kinetic energy of the particles after the collision.**

P+ + P+ + kinetic energy (of protons) →P+ + P+ + π + π + π + kinetic energy

*So in effect the kinetic energy beforehand went into producing 3 pions, and whatever was left over became the kinetic energy of those pions plus protons.*

*So to find this kinetic energy we need to subtract the energy required to make the 3 pions away from the original kinetic energy.*

Kinetic energy beforehand = 2 GeV = (2 × 109) (1.6 × 10-19) = 3.2 × 10-10 Joules

Energy required to produce 3 pions: E = 3*mc*2 = 3(2.4842 × 10–28)( 2.9979 × 108)2

= 6.6981 × 10–11 Joules

Kinetic energy after collision = (3.2 × 10-10) - (6.6981 × 10–11) = 2.53 × 10–10 J

1. **Calculate the maximum number of pions that *could* have been created during the collision.**

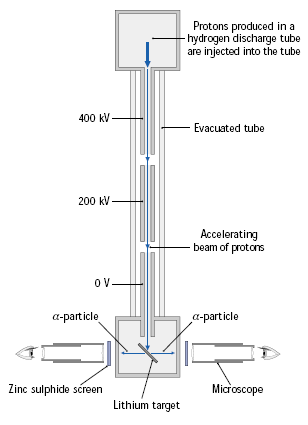
Kinetic energy beforehand = 3.2 × 10-10 Joules

Energy required to produce *1* pion = *mc*2 = (2.4842 × 10–28)( 2.9979 × 108)2 = 2.2327 × 10–11 Joules

Number of pions = = 14.35

So the maximum number that *could* have been created is 14 pions.

**2007 Question 10 (a)**



1. **Draw a labelled diagram to show how Cockcroft and Walton accelerated the protons.**

See diagram.

1. **What is the velocity of a proton when it is accelerated from rest through a potential difference of 700 kV?**

= = 1.16 × 107 m s-1

1. **Write a nuclear equation to represent the disintegration of a lithium nucleus when bombarded with a proton.**

+

(accept α for *He* )

1. **Calculate the energy released in this disintegration.**

Mass beforehand (mass of reactants) = 1.1646 × 10-26 + 1.6726 × 10-27 = 1.33186 × 10-26 kg

Mass afterwards (mass of products) = 2(6.6443 × 10-27) = 1.32886 × 10-26 kg

Loss in mass = 1.33186 × 10-26 kg - 1.32886 × 10-26 kg = 3.00 × 10-29 kg

*E* = *mc2* or = (3.00 × 10-29)(9 × 1016) = *E* = 2.7 × 10-12 J

1. **Compare the properties of an electron with that of a positron.**

Both have equal mass / charges equal / charges opposite in sign

1. **What happens when an electron meets a positron?**

Pair annihilation occurs.

1. **How did Fermi’s theory of radioactive decay resolve this?**

Fermi (and Pauli) realised that another particle must be responsible for the missing momentum, which they called the neutrino.

**2006 Question 10 (a)**

1. **What is a photon?**

A photon is a discrete amount of electromagnetic radiation.

1. **Calculate the frequency of a photon produced during the interaction.**

The equation for pair annihilation is as follows:

To calculate the frequency we first need to establish how much mass gets ‘annihilated’ and then calculate how much energy that releases.Mass of particles beforehand = mass of proton + mass of antiproton

= 2(1.673 × 10-27) = 3.346 × 10-27 kg

The energy released is calculated from *E = mc2*

*E* = (3.346 × 10-27 )(2.998 × 108)2 = 3.0074 × 10-10 J

This is the energy that now becomes associated with two photons.

So energy associated with *one* photon = 1.5037 × 10-10 J

We then use *E = hf*  *f* = 2.2694 × 1023 Hz

1. **Why are two photons produced?**

So that momentum is conserved.

1. **Describe the motion of the photons after the interaction.**

They move in opposite directions.

1. **How is charge conserved during this interaction?**

Total charge before = +1-1 = 0

Total charge after = 0 since photons have zero charge

1. **After the annihilation, pairs of negative and positive pions are produced. Explain why.**

The energy of the photons is converted into matter .

1. **Give the quark composition of (i) a positive pion, (ii) a negative pion.**

π+ = up and anti-down

π- = down and anti-up

1. **List the fundamental forces of nature that pions experience.**

Electromagnetic, strong, weak , gravitational

1. **What is the half-life of a neutral pion?**

T1/2 = 2.8 ×10-13 seconds

**2005 Question 11 (a)**

1. **What is the structure of an alpha particle?**

An alpha particle is identical to a helium nucleus (2 protons and 2 neutrons).

1. **What conclusion did he form about the structure of the atom?**

The atom was mostly empty space with a dense positively-charged core and with negatively-charged electrons in orbit at discrete levels around it.

1. **High voltages can be used to accelerate alpha particles and protons but not neutrons.Explain why.**

Alpha particles and protons are charged, neutrons are not.

1. **Copy and complete the following nuclear equation for this reaction.**

** +  → ** + K.E.

1. **Give an advantage of circular accelerators over linear accelerators.**

Circular accelerators result in progressively increasing levels of energy and occupy much less space than an equivalent linear accelerator.

1. **Explain why new particles are produced.**

The kinetic energy of the two protons gets converted into mass.

1. **List the six flavours of quark.**

Up, down, strange, charm, top and bottom.

1. **Give the quark composition of the proton.**

Up, up, down.

**2004 Question 10 (a)**

1. **List two other fundamental forces of nature and give one property of each force.**

Strong nuclear force: acts on nucleus/protons + neutrons/hadrons/baryons/mesons, short range

Gravitational force: attractive force, inverse square law/infinite range, all particles

Electromagnetic force: acts on charged particles, inverse square law/infinite range

1. **Write a nuclear equation for this decay.**
2. **Calculate the energy released during the decay of a neutron.**

Mass before = mass of neutron = 1.6749 × 10–27 kg

Mass after = mass of proton + mass of electron

= 1.6726 × 10–27 + 9.1094 × 10–31 = 1.6817 × 10–27 kg

Loss in mass (mass defect) = (1.6749 × 10–27 kg) – (1.6817 × 10–27 kg)

= 1.3891 × 10-30 kg

E = mc2 = (1.3891 × 10-30)(2.9979 × 108)2 = 1.25 × 1013 J

1. **Explain how the existence of the neutrino, which was first named by Enrico Fermi, resolved this.**

Momentum and energy are conserved when the momentum and energy of the associated neutrino are taken into account.

1. **What is nuclear fission?**

Fission is the splitting of a large nucleus into two smaller nuclei with the release of energy.

1. **What is the function of the moderator in the reactor?**

It slows down the fast neutrons (so that they in turn can be captured by the uranium atoms and cause the uranium nuclei to undergo fission).

1. **How did the cadmium rods control the rate of fission?**

They absorbed the neutrons which would otherwise cause fission.

**2003 Question 10 (a)**

1. **Leptons, baryons and mesons belong to the “particle zoo”.**

Give (i) an example, (ii) a property, of each of these particles.

LEPTONS; electron, positron, muon , tau, neutrino

Not subject to strong nuclear force

BARYONS; proton, neutron

Subject to all forces, three quarks

MESONS pi(on), kaon

Subject to all forces, mass between electron and proton, quark and antiquark

1. **Calculate the minimum frequency of the γ-ray photon required for this reaction to occur.**

*The energy associated with the gamma ray photon (E = hf) needs to be equal to the energy associated with 2 electrons (E = 2mc2)*

*hf* = *2mc2*

(6.6 × 10–34)(*f*) = 2(9.1 × 10–31)( 3.0 × 108)2

*f* =2.5×1020 Hz

1. **What is the effect on the products of the reaction if the frequency of the γ-ray photon exceeds the minimum value?**

The electrons which were created would move off with greater speed.

There may also be more particles produced.

1. **Write a reaction that represents pair annihilation.**

e+ + e- → 2γ

1. **Explain how the principle of conservation of charge and the principle of conservation of momentum apply in pair annihilation.**

Charge:

The *net* charge of the electron and positron is 0, and there is no charge associated with the gamma ray photons.

Momentum:

The electron and positron are moving directly towards each other, so net momentum beforehand = 0, and afterwards the two photons move in opposite directions so net momentum after = 0.

**2002 Question 10 (a)**

1. **Name the four fundamental forces of nature.**

Gravitational, Electromagnetic, Strong nuclear, Weak nuclear

1. **Which force is responsible for binding the nucleus of an atom?**

Strong

1. **Give two properties of this force.**

Short range, act on nucleons, binds nucleus, strongest of all the forces

1. **Outline this experiment.**

Protons are released at the top of the accelerator and get accelerated across a potential difference of 800 kVolt.

These protons collide with a lithium nucleus at the bottom, and as a result two alpha particles are produced.

The alpha particles move off in opposite directions at high speed.

They then collide with a zinc sulphide screen, where they cause a flash and get detected by microscopes.

1. **Write a nuclear equation to represent this reaction.**
2. **Calculate the energy released in this reaction.**

Mass before = [(1.6730 × 10-27) + (1.1646 × 10-26)]

Mass after = [2(6.6443 × 10-27)]

Mass defect = mass before – mass after

Mass defect = 3.0 x 10-29 kg

Using E = mc2  E = (3.0 x 10-29)( 3.00 × 108)2   E = 2.7 × 10-12 J