Absorption spectrum  when a continuous spectrum of light is shone through an element in gaseous form, specific frequencies are preferentially absorbed (the frequencies of the element’s emission spectrum). The resulting spectrum is a continuous spectrum with dark lines (i.e. most frequencies with some specific ones missing) and is known as the element’s absorption spectrum.

Alpha (α) decay  occurs when an unstable nuclide emits a particle of the same configuration as a helium nucleus, $^4\text{He}$ (two protons and two neutrons). Alpha particles have a very short range in air and are absorbed by thin paper.

Background radiation  the radiation present around us, most of which is from natural sources such as cosmic rays, rocks and soil, and vegetation. A small part is from artificial sources such as medical equipment and nuclear power.

Baryon  a type of hadron that consists of three quarks. Examples are protons, antiprotons, and neutrons.

Baryon number (B)  all baryons have a baryon number of +1 and all antibaryons have a baryon number of −1. All other particles have a baryon number of 0. Baryon number is conserved in all reactions.

Beta (β) decay  this can be either negative beta (β−) decay where an unstable nuclide emits an electron, or positron (β+) decay where an unstable nuclide emits a positron (the antiparticle of an electron which has a positive charge). Beta particles have a range of several centimetres in air and are absorbed by a few millimetres of aluminium.

Boson (or exchange particle)  a “virtual” particle that mediates (or transmits) the force between a pair of particles. Each of the four forces (gravitational, weak nuclear, electromagnetic, and strong nuclear) have different bosons.

Charge, conservation of  charge is conserved in any interaction between particles or their decay.

Electromagnetic force  has an infinite range, but is much stronger at short distances. It acts between all charged particles, holding atoms and charged particles together as well as causing electric and magnetic fields.

Emission spectrum  when an element is hot enough (given enough energy) it emits light. Analysis of this light shows that each element only emits specific frequencies (discrete spectral lines). These specific frequencies form the element’s emission spectrum.

Energy levels  electrons occupy discrete energy levels with specific energies, and electrons can only move between these levels if they absorb or emit energy that equals the difference in the energy levels it is moving between.

Excited state  any state that an electron occupies that is at an energy level higher than the ground state.

Feynman diagrams  are graphic visualisations that represent interactions between particles.

Gamma ray (γ) emission  photons of high-energy electromagnetic radiation that often accompany other decay mechanisms. Gamma rays have a range of many metres in air and are absorbed by several centimetres of lead.

Gravitational force  has an infinite range and acts on all particles. It is always attractive and over astronomical distances it is the dominant force.

Hadron  a particle composed of quarks, which can be further classified as either a baryon (three quarks) or a meson (quark-antiquark pair). Protons and neutrons are hadrons.

Half-life  the time taken for half the total number of nuclei initially in a sample to decay, or alternatively, for the initial activity of a sample to fall by half.

Higgs boson  an elementary particle that explains the process by which particles can acquire mass.

Lepton  an elementary particle of the electron family, which consists of the electron (e−), muon (μ), tau (τ), their antiparticles, plus six neutrinos associated with each of the particles and antiparticles.

Lepton number (L)  all leptons have a lepton number of +1 and antileptons have a lepton number of −1. Lepton number is conserved in all reactions.
Vocabulary

Mass defect the difference between the mass of a nucleus and the masses of its component nucleons. The total mass of the individual nucleons making up a nucleus must be greater than the mass of that nucleus.

Mass–energy relationship, Einstein’s when work is done on a system, its energy increases by an amount ΔE (J) and so its mass will increase by an amount Δm (kg) given by ΔE = Δmc², where c (m s⁻¹) is the speed of electromagnetic waves in a vacuum.

Meson a type of hadron that consists of a quark-antiquark pair. Examples are pions and kaons.

Nuclear binding energy the energy that is needed to deconstruct a nucleus from its nucleons, and the energy that is released when a nucleus is assembled from its component nucleons.

Nuclear fission a nuclear reaction in which large nuclei are split into small nuclei and energy is released.

Nuclear fusion a nuclear reaction in which the joining together (or fusing) or small nuclei into larger nuclei releases energy. Nuclear fusion occurs in the Sun.

Photon energy–frequency relationship the energy E (J) of a photon is equal to the frequency f (Hz) of the radiation multiplied by the Planck constant h, E = hf. Using the wave equation (c = fλ) this can be expressed as E = hfc, where c (m s⁻¹) is the speed of electromagnetic waves in a vacuum and λ (m) is the wavelength of the photon.

Planck constant (h) is equal to 6.63 × 10⁻³⁴ J s.

Quark the elementary particle that makes up all hadrons (baryons and mesons). There are six different types of quark: up, down, charm, strange, top, and bottom.

Quark confinement means that isolated quarks cannot be observed. If sufficient energy is supplied to a hadron in order to attempt to isolate a quark, then more hadrons will be produced rather than isolated quarks.

Radioactive decay the spontaneous emission of ionizing radiations (alpha, beta, or gamma) from an unstable nucleus. It is a random, spontaneous process, and the rate of decay decreases exponentially with time. The nuclide decaying is the parent and the nuclide(s) formed are the daughter(s).

Strangeness, conservation of strangeness is not conserved when strange particles decay through the weak interaction. Strangeness is conserved when there is a strong interaction.

Strong nuclear force (strong interaction) has a very short range (≈10⁻¹⁵ m) at which it is attractive but at distances smaller than this it becomes strongly repulsive. The strong nuclear force acts between hadrons but not leptons, binding protons and neutrons together in the nucleus.

Unified atomic mass unit (u) a unit for masses measured on the atomic scale and is one-twelfth of the rest mass of an unbound atom of carbon-12 in its nuclear and electronic ground state. One unified atomic mass unit is equivalent to 1.661 × 10⁻²⁷ kg.

Weak nuclear force (weak interaction) has a very short range (≈10⁻¹⁸ m) and acts between all particles. It is responsible for radioactive decay and neutrino interaction.
Mass defect and binding energy

Useful information

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Unified atomic mass unit, u</td>
<td>$1.66 \times 10^{-27}$ kg = 931.5 MeV c$^{-2}$</td>
</tr>
<tr>
<td>Speed of light, $c$</td>
<td>$3.00 \times 10^8$ ms$^{-1}$</td>
</tr>
<tr>
<td>Electron rest mass, $m_e$</td>
<td>0.000549 u</td>
</tr>
<tr>
<td>Neutron rest mass, $m_n$</td>
<td>1.008665 u</td>
</tr>
<tr>
<td>Proton rest mass, $m_p$</td>
<td>1.007276 u</td>
</tr>
<tr>
<td>Electronvolt, eV</td>
<td>$1.60 \times 10^{-19}$ J</td>
</tr>
</tbody>
</table>

Questions

1. The rest mass of a $^4_2$He nucleus is 4.0015 u. Calculate the binding energy of a helium nucleus
   a. in megaelectronvolts, MeV

   ____________________________________________________________
   ____________________________________________________________
   ____________________________________________________________
   ____________________________________________________________
   ____________________________________________________________

   b. in joules, J.

   ____________________________________________________________
   ____________________________________________________________
   ____________________________________________________________
   ____________________________________________________________
   ____________________________________________________________

2. Calculate the binding energy per nucleon, in MeV, for an iron-56 nuclide.
   rest mass of $^{56}_{26}$Fe nucleus = 55.9207 u

   ____________________________________________________________
   ____________________________________________________________
   ____________________________________________________________
   ____________________________________________________________
   ____________________________________________________________

   a. Calculate the binding energy per nucleon, in MeV, for an iron-56 nuclide.
7.2 Nuclear reactions

b Calculate the binding energy per nucleon, in MeV, for a uranium-238 nuclide.

rest mass of $^{238}\text{U}$ nucleus = 238.0003 u

c Sketch a graph showing how the average binding energy per nucleon varies with nucleon number

- marking on the two nuclides mentioned in 2 a and b
- indicating the most stable nuclides
- indicating which nuclides are most likely to undergo fission
- indicating which nuclides are most likely to undergo fusion.

3 A carbon-14 nucleus decays by $\beta^-$ emission to a nitrogen-14 nucleus.

rest mass of $^{14}\text{C}$ = 14.00324 u  rest mass of $^{14}\text{N}$ = 14.00307 u

a Write out the nuclear equation of the reaction.

b Calculate the energy released by the reaction, in joules, per carbon-14 nucleus.

c Calculate the mass of carbon-14 which would need to decay in order to release 100 MJ of energy.
4 A deuteron (mass = 2.0141 u), of negligible kinetic energy, is absorbed by a lithium-6 nucleus (mass = 6.0135 u) and the compound nucleus disintegrates spontaneously into two α particles. Calculate the average energy, in joules, provided to each α particle.

rest mass of α particle = 4.0015 u


5 A fusion reaction in which deuterium and tritium nuclei fuse together to form a helium nucleus is represented by

\[ _{1}^{2}\text{H} + _{1}^{3}\text{H} \to _{2}^{4}\text{He} + _{0}^{1}\text{n} \]

and releases \(2.88 \times 10^{-12}\) J of energy. Calculate the mass of the helium nucleus produced.

rest mass of deuterium nucleus = \(3.345 \times 10^{-27}\) kg
rest mass of tritium nucleus = \(5.007 \times 10^{-27}\) kg
rest mass of neutron = \(1.675 \times 10^{-27}\) kg


6 a rest mass of U-235 = 235.0439 u      rest mass of U-236 = 236.0456 u
rest mass of U-238 = 238.0508 u      rest mass of U-239 = 239.0543 u

Find the energy difference, MeV, between

i uranium-235 + neutron and uranium-236

ii uranium-238 + neutron and uranium-239.

b Use your results from 6 a to explain why uranium-235 is more fissionable than uranium-238.
7.2 Nuclear reactions

7 A common fission reaction is shown below.

\[ {}^{235}\text{U} + {}^{1}\text{n} \rightarrow {}^{141}\text{Ba} + {}^{92}\text{Kr} + {}^{3}\text{n} \]

rest mass of U-235 = 235.0439 u
rest mass of Ba-141 = 140.9144 u
rest mass of Kr-92 = 91.9262 u

Calculate

a the energy released, in joules, by one such fission reaction

b the energy available from the complete fission of 1.00 g of uranium-235.
Classification of particles

1. a) Identify the hadrons, leptons, baryons and mesons amongst these particles:
   
   \[ p, n, \bar{\nu}_e, \bar{e}, \mu, \pi^0, K^+ \]
   
   hadrons: ____________________________________________________________
   leptons: ___________________________________________________________
   baryons: __________________________________________________________
   mesons: __________________________________________________________

   b) State which of the above particles are
   
   i) antiparticles: ______________________________________________________
   ii) charged particles: ________________________________________________

2. Quarks may be combined together in a number of ways within the hadron family.
   
   Name the two branches of the hadron family and their possible general quark composition using \( q \) to denote a quark and \( \bar{q} \) to denote an antiquark.
   
   name: __________________________________________________________________
   quark composition: __________________________________________________________________
   name: __________________________________________________________________
   quark composition: __________________________________________________________________

3. State two ways in which hadrons differ from all other subatomic particles.
   
   __________________________________________________________
   __________________________________________________________

4. Give the quark composition of the following particles.
   
   a) neutron: __________________________________________________________
   b) proton: __________________________________________________________
Decide whether the statements about neutrons and antineutrons are true or false.

<table>
<thead>
<tr>
<th>Statement</th>
<th>True/False</th>
</tr>
</thead>
<tbody>
<tr>
<td>a an antineutron has a charge of $1.60 \times 10^{-19}$ C</td>
<td></td>
</tr>
<tr>
<td>b an antineutron is not a fundamental particle</td>
<td></td>
</tr>
<tr>
<td>c an antineutron has a rest mass of $1.675 \times 10^{-27}$ kg</td>
<td></td>
</tr>
<tr>
<td>d a neutron is a fundamental particle</td>
<td></td>
</tr>
<tr>
<td>e a neutron has a rest mass of $1.675 \times 10^{-27}$ kg</td>
<td></td>
</tr>
<tr>
<td>f a neutron has no charge</td>
<td></td>
</tr>
</tbody>
</table>

An antimuon may decay in the following way:

$$\bar{\mu} \rightarrow \bar{e} + \nu_e + \bar{\nu}_\mu$$

a Replace each particle/antiparticle with its corresponding antiparticle/particle to complete the equation showing how a muon may decay.

$$\mu \rightarrow$$

b State one difference and one similarity between a muon and an electron.

difference: 

similarity: 
7 Atomic, nuclear and particle physics

7.3 The structure of matter

Name: ……………………………… Date: ………………………………

Conservation rules

1 a The following equation represents the emission of a positron from a proton:

\[ p \rightarrow n + \bar{e} + \nu_e \]

Mass–energy and momentum are conserved in this emission. Which of the following quantities are also conserved?

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Conserved (✓ or ✗)</th>
</tr>
</thead>
<tbody>
<tr>
<td>i charge (Q)</td>
<td></td>
</tr>
<tr>
<td>ii baryon number (B)</td>
<td></td>
</tr>
<tr>
<td>iii lepton number (L)</td>
<td></td>
</tr>
<tr>
<td>iv strangeness (S)</td>
<td></td>
</tr>
</tbody>
</table>

b In positron emission an up quark undergoes the following change:

\[ u \rightarrow d + \bar{e} + \nu_e \]

Show that charge, lepton number and baryon number are conserved in this decay.

________________________________________________________________________________________
________________________________________________________________________________________
________________________________________________________________________________________

2 The neutral kaon, \( K^0 \), is a meson of strangeness +1. For the decay equation

\[ K^0 \rightarrow \pi^+ + \pi^- \]

indicate whether the following quantities are conserved:

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Conserved (✓ or ✗)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a charge (Q)</td>
<td></td>
</tr>
<tr>
<td>b baryon number (B)</td>
<td></td>
</tr>
<tr>
<td>c lepton number (L)</td>
<td></td>
</tr>
<tr>
<td>d strangeness (S)</td>
<td></td>
</tr>
</tbody>
</table>
3. Use the conservation rules to decide whether each of the following decays is feasible. Give a reason for your answers.

a. \( \pi^- \rightarrow \bar{e} + \nu_e \)

b. \( \pi^- \rightarrow p + e + \bar{e} \)

4. The negative kaon, \( K^- \), has a strangeness of \(-1\), and may decay into a muon and a muon antineutrino according to:

\[ K^- \rightarrow \mu + \bar{\nu}_\mu \]

a. Complete the following table classifying the particles involved. Use ticks and crosses as indicated in the first row.

<table>
<thead>
<tr>
<th></th>
<th>( K^- )</th>
<th>( \mu )</th>
<th>( \bar{\nu}_\mu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>charged particle</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>hadron</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>meson</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>baryon</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>lepton</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

b. For the decay in part a, charge is conserved. State one other quantity that is conserved and a quantity that is not conserved in the decay.

quantity conserved: ____________________________

quantity not conserved: ____________________________
7 Atomic, nuclear and particle physics

7.3 The structure of matter

Feynman diagrams

Draw a Feynman diagram for each situation described below, with space/position on the $x$-axis and time on the $y$-axis as described on page 300 of the student book.

1. $\beta^-$ decay: $n \rightarrow p + e^- + \bar{v}_e$
   - in terms of the particles indicated in the equation
   - in terms of quark transformations
7.3 The structure of matter

2  $\beta^+ \text{ decay: } p \rightarrow n + \bar{\nu} + \nu_e$

3  $\text{electron capture: } p + e \rightarrow n + \nu_e$

4  $\text{electrostatic repulsion between two electrons}$
5  interaction between a neutron and an electron neutrino: \( n + \nu_e \rightarrow p + e \)

6  interaction between a proton and an electron antineutrino: \( p + \bar{\nu}_e \rightarrow n + \bar{e} \)

7  collision between a proton and an electron: \( p + e \rightarrow n + \nu_e \)
7.3 The structure of matter

8 strong nuclear force between a neutron and a proton
Alpha Decay

1. The diagram shows part of a chart of Z vs N for all known nuclei.

(a) Circle Thorium 232 on the chart
(b) How many Neutrons does $^{232}Th$ have
(c) Name an isotope of $^{232}Th$
(d) Draw an arrow from the $^{232}Th$ square to the isotope that it would decay into if it emitted an alpha particle.
(e) Write an equation for the decay of $^{232}Th$

2. Name two ways of detecting an alpha particle.

3. The table gives some atomic masses. Use the information to calculate the energy of the alpha particle in the decay of $^{232}Th$

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Mass / U</th>
</tr>
</thead>
<tbody>
<tr>
<td>He 4</td>
<td>4.00260</td>
</tr>
<tr>
<td>Th 232</td>
<td>232.038051</td>
</tr>
<tr>
<td>Ac 228</td>
<td>228.031014</td>
</tr>
<tr>
<td>Ra 228</td>
<td>228.031064</td>
</tr>
</tbody>
</table>

Formulae

$E=mc^2$

$1U = 931\text{MeV}$
Atomic models

1. Give two pieces of evidence that supports the theory that matter is made of atoms.

2. According to the Thomson model of the Atom (plum pudding/currant bun) what was the expected result of the Rutherford experiment?

3. A beam of electrons are projected into an electric field as shown. Calculate the force on an electron and draw a possible path of the electron.

4. Why can’t electrons orbit the nucleus in circular paths?

<table>
<thead>
<tr>
<th>Formulae</th>
</tr>
</thead>
<tbody>
<tr>
<td>E=V/d</td>
</tr>
<tr>
<td>F=Eq</td>
</tr>
<tr>
<td>e = 1.6x10^{-19} C</td>
</tr>
</tbody>
</table>
Beta Decay

1. The diagram shows part of the chart of Z vs N for all known nuclides.

![Diagram of Z vs N chart]

(a) There are 7 different types of Be, what are these called?

(b) Identify $^{14}_{6}C$ by on the chart by putting a circle round it.

(c) $^{14}_{6}C$ decays by emission of beta radiation, draw an arrow on the chart to show what it decays into.

2. Why does the fact that beta particles have a range of KE necessitate the existence of the neutrino?

3. The diagram shows a cloud chamber photograph taken in a region of strong magnetic field. Track A was made by an electron.

(a) In which direction is the magnetic field?

(b) What particle made track B?
Binding Energy

1. Define the term binding energy.

2. Consider a 24g block of carbon 12.
   (a) Calculate the number atoms in the block.
   (b) Calculate the number of nucleons in the block.
   (c) Estimate the amount of energy released if all the mass of the block turned into energy.

3. Sketch the BE/nucleon vs Atomic mass curve on the axes provided. Include approximate scales for the axes.

4. Using the symbols in the table write an equation for the BE of $^{14}_6C$.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon 14 nucleus</td>
<td>$M_{14}$</td>
</tr>
<tr>
<td>Neutron</td>
<td>$m_n$</td>
</tr>
<tr>
<td>Proton</td>
<td>$m_p$</td>
</tr>
<tr>
<td>Speed of light</td>
<td>$c$</td>
</tr>
</tbody>
</table>
Electron energy levels

1. What is the approximate wavelength of visible light?

2. A photon of visible light has frequency $600 \times 10^{12}$ Hz. Calculate the energy of the photon.

3. The diagram shows the energy levels in a hypothetical atom.
   (a) How much energy in Joules is released when the electron makes the smallest transition?
   (b) How many different lines would there be in the spectrum produced by this atom?

4. Explain why lines are missing in the spectrum from a white light source when it is passed through hydrogen gas as shown.

Formulae

\[
E = hf \\
h = 6.6 \times 10^{-34} \text{ Js} \\
E = Vq \\
e = 1.6 \times 10^{-19} \text{ C}
\]
Exponential Decay

1. The diagram shows an exponential decay curve plotted in LoggerPro.

(a) From the graph estimate the half life of the decay.

(b) When there are 37 nuclei the rate of decay = 17 decays/s. Calculate the rate of decay when there are 15 Nuclei.

(c) From the information on the graph find the decay constant.

(d) Use the decay constant to calculate the half life.

2. A sample of a radioactive isotope decays at a rate of 100 decays per second. If the half life of the material is 2 years how long will it take before the decay rate is 25 decays per second?

Formulae

\[ N = N_0e^{-\lambda t} \]

\[ \lambda = \frac{ln2}{t_{1/2}} \]
Fission and fusion

1. Consider the following nuclear reaction.

\[ ^{236}_{92}U \rightarrow ^{92}_{36}Kr + ^{141}_{56}Ba + ? n_0 \]

(a) What type of reaction is this?

(b) Calculate how many neutrons must be emitted.

(c) Mark the positions of U, Kr and Ba on the Binding energy/nucleon curve below and use it to explain why energy is released during this reaction.

(d) Use the curve to estimate the energy released

2. Explain why fusion doesn’t take place between nuclei in the Earth’s atmosphere?
Fundamental particles

<table>
<thead>
<tr>
<th>Particle</th>
<th>quarks</th>
<th>Baryon number</th>
<th>Strangeness</th>
<th>Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>ddu</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>p⁺</td>
<td>uud</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Σ⁻</td>
<td>dds</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>uuu</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>uud</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>udd</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ddd</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Particle</th>
<th>quarks</th>
<th>Baryon number</th>
<th>Strangeness</th>
<th>Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>π⁺</td>
<td>ud</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>π⁻</td>
<td>üd</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quark</th>
<th>Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>+2/3</td>
</tr>
<tr>
<td>d</td>
<td>-1/3</td>
</tr>
<tr>
<td>s</td>
<td>-1/3</td>
</tr>
<tr>
<td>c</td>
<td>+2/3</td>
</tr>
<tr>
<td>b</td>
<td>-1/3</td>
</tr>
<tr>
<td>t</td>
<td>+2/3</td>
</tr>
</tbody>
</table>

1. Fill in the baryon number, strangeness and charge for the particles in the tables above.

2. The last three particles are all Δ particles. Δ⁺, Δ⁺⁺, Δ, Δ⁰. Put the names in the correct rows.

3. Show that baryon number and charge are conserved in the following interactions
   \[ \Sigma^- \rightarrow n + \pi^- \]
   \[ \Delta^{++} \rightarrow p + \pi^+ \]
   \[ \Delta^- \rightarrow n + \pi^- \]

4. Why isn’t strangeness number conserved in the first interaction?
Particle interactions

1. Put the following particles in the correct column of the table:
   - Neutron
   - Proton
   - Electron
   - Neutrino

<table>
<thead>
<tr>
<th>Hadron</th>
<th>Lepton</th>
</tr>
</thead>
</table>

2. Put the following forces in order of increasing strength:
   - Electromagnetic
   - Gravity
   - Weak
   - Strong

3. What is the name of the exchange particle responsible for electromagnetic interactions?

4. State the name of the particles A and B in the Feynman diagram.

5. Explain why the following Feynman diagrams are impossible.

The Nucleus

1. What is the approximate size of an atomic nucleus?

2. What is the approximate value of atomic radius/nuclear radius?

3. The table gives the mass of 10 boxes containing different numbers of small balls. The mass of the box is 100g. Deduce the mass of one ball.

<table>
<thead>
<tr>
<th>Mass of box+balls /g</th>
</tr>
</thead>
<tbody>
<tr>
<td>2600</td>
</tr>
<tr>
<td>3100</td>
</tr>
<tr>
<td>3125</td>
</tr>
<tr>
<td>2500</td>
</tr>
<tr>
<td>2550</td>
</tr>
<tr>
<td>2650</td>
</tr>
<tr>
<td>2975</td>
</tr>
<tr>
<td>2575</td>
</tr>
<tr>
<td>3075</td>
</tr>
</tbody>
</table>

4. Define the term isotope.

5. How many neutrons does a $^{13}_6C$ nucleus have?

6. Give one reason why we think that the nuclear force is strong.
Questions

1 (IB)

a) Light is emitted from a gas discharge tube. Outline briefly how the visible line spectrum of this light can be obtained. The table below gives information relating to three of the wavelengths in the line spectrum of atomic hydrogen.

<table>
<thead>
<tr>
<th>Wavelength / 10⁻⁹ m</th>
<th>Photon energy / 10⁻¹⁹ J</th>
</tr>
</thead>
<tbody>
<tr>
<td>1880</td>
<td>1.06</td>
</tr>
<tr>
<td>656</td>
<td>3.03</td>
</tr>
<tr>
<td>486</td>
<td>4.09</td>
</tr>
</tbody>
</table>

b) Deduce that the photon energy for the wavelength of 486 \times 10⁻⁹ m is 4.09 \times 10⁻¹⁹ J.

The diagram below shows two of the energy levels of the hydrogen atom, using data from the table above. An electron transition between these levels is also shown.

\[ \text{photon emitted, wavelength = 656 nm} \rightarrow -2.41 \times 10⁻¹⁹ J \]
\[ \text{photon emitted, wavelength = 486 nm} \rightarrow -5.44 \times 10⁻¹⁹ J \]

b) On a copy of the diagram above, construct the other energy level needed to produce the energy changes shown in the table above.

(ii) Draw arrows to represent the energy changes for the two other wavelengths shown in the table above.

3 (IB) A nucleus of the isotope xenon, Xe-131, is produced when a nucleus of the radioactive isotope iodine I-131 decays.

a) Explain the term isotopes.

b) Fill in the boxes on a copy of the equation below in order to complete the nuclear reaction equation for this decay.

\[ \boxed{^{131}\text{I} \rightarrow ^{131}\text{Xe} + \beta^- + \boxed{}} \]

c) The activity \( A \) of a freshly prepared sample of the iodine isotope is \( 3.2 \times 10^5 \) Bq. The variation of the activity \( A \) with time \( t \) is shown below.

On a copy of this graph, draw a best-fit line for the data points.

d) Use the graph to estimate the half-life of I-131.
4 (IB) One isotope of potassium is potassium-42 ($^{42}_{19}$K). Nuclei of this isotope undergo radioactive decay with a half-life of 12.5 hours to form nuclei of calcium.

a) Complete a copy of the nuclear reaction equation for this decay process.

\[ ^{42}_{19}K \rightarrow ^{20}_{8}Ca + \]

b) The graph below shows the variation with time of the number $N$ of potassium-42 nuclei in a particular sample.

![Graph showing the decay of potassium-42 nuclei over time.]

The isotope of calcium formed in this decay is stable.

On a copy of the graph above, draw a line to show the variation with time $t$ of the number of calcium nuclei in the sample.

c) With reference to the graph, explain why energy can be released in both the fission and the fusion processes. (5 marks)

5 (IB)

a) Explain what is meant by a nucleon.

b) Define what is meant by the binding energy of a nucleus.

The plot below shows the variation with nucleon number of the binding energy per nucleon.

![Graph showing the variation of binding energy per nucleon with nucleon number.]

7 a) Distinguish between nuclear fission and radioactive decay.

b) A nucleus of uranium-235 ($^{235}_{92}$U) may absorb a neutron and then undergo fission to produce nuclei of strontium-90 ($^{90}_{38}$Sr) and xenon-142 ($^{142}_{54}$Xe) and some neutrons.
The strontium-90 and the xenon-142 nuclei both undergo radioactive decay with the emission of β⁻ particles.

(i) Write down the nuclear equation for this fission reaction.

(ii) State the effect, if any, on the nucleon number and on the proton number of a nucleus when the nucleus undergoes β⁻ decay.

(6 marks)

8 a) A neutron collides with a nucleus of uranium-235 and the following reaction takes place.

\[ ^{235}_{92}U + ^{1}_{0}n \rightarrow ^{96}_{51}Rb + ^{138}_{55}Cs + 2^{1}_{0}n \]

State the name of this type of reaction.

b) Using the data below, calculate the energy, in MeV, that is released in the reaction.

- mass of \(^{235}_{92}U\) nucleus = 235.0439u
- mass of \(^{96}_{51}Rb\) nucleus = 95.9342u
- mass of \(^{138}_{55}Cs\) nucleus = 137.9112u
- mass of \(^{1}_{0}n\) nucleus = 1.0087u

c) Suggest the importance of the two neutrons released in the reaction.

d) The rest mass of each neutron accounts for about 2 MeV of the energy released in the reaction. Explain what accounts for the remainder of the energy released.

(9 marks)

9 The diagram below illustrates a proton decaying into a neutron by beta positive (\(\beta^+\)) decay.

![Diagram showing proton decaying into neutron by beta positive decay](image)

State the name of:

a) the force involved in this decay
b) the particle X
c) the particle Y involved in the decay.

(3 marks)

10 a) Possible particle reactions are given below. In each case apply the conservation laws to determine whether or not the reactions violate any of them.

(i) \(\mu \rightarrow e + \gamma\)
(ii) \(p + n \rightarrow p + \pi^0\)
(iii) \(p \rightarrow \pi^+ + \pi\)

b) State the name of an exchange particle involved in the weak interaction.

(10 marks)

11 (IB) When a negative kaon (\(K^-\)) collides with a proton, a neutral kaon (\(K^0\)), a positive kaon (\(K^+\)) and a further particle (X) are produced.

\[ K^- + p \rightarrow K^0 + K^+ + X \]

The quark structure of kaons is shown in the table.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Quark structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K^-)</td>
<td>(s\bar{u})</td>
</tr>
<tr>
<td>(K^+)</td>
<td>(u\bar{s})</td>
</tr>
<tr>
<td>(K^0)</td>
<td>(d\bar{s})</td>
</tr>
</tbody>
</table>

a) State the family of particles to which kaons belong.

b) State the quark structure of the proton.

c) The quark structure of particle X is sss. Show that the reaction is consistent with the theory that hadrons are composed of quarks.

(4 marks)

12 The Feynman diagram below represents a \(\beta^\) decay via the weak interaction process. Time is shown as upwards. The wiggly line represents a virtual exchange particle.

![Feynman diagram](image)

a) State what is meant by virtual exchange particle.

b) Determine whether the virtual particle in the process represented by the Feynman diagram is a \(W^+\), a \(W^-\), or a \(Z^0\) boson.

(4 marks)
45 Using the basic weak interaction vertex involving a W boson and two quarks and leptons given in Figure 7.30, state three possible ways in which the W boson can decay.

46 Using the basic weak interaction vertex involving a Z boson and two quarks and leptons given in Figure 7.30, draw Feynman diagrams to represent the following processes:
   a  \( e^- + e^+ \rightarrow \nu_\mu + \bar{\nu}_\mu \)
   b  \( e^- + \nu_\mu \rightarrow e^- + \nu_\mu \)
   c  \( e^- + e^+ \rightarrow e^- + e^- \)

Exam-style questions

1. How would the decay of a nucleus of \(^{60}\text{Co}\) into a nucleus of \(^{60}\text{Ni}\) be described?
   - A  alpha decay
   - B  beta minus decay
   - C  beta plus decay
   - D  gamma decay

2. What are the number of neutrons and the number of electrons in the neutral atom of \(^{195}\text{Pt}\)?

<table>
<thead>
<tr>
<th>Number of neutrons</th>
<th>Number of electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 17</td>
<td>195</td>
</tr>
<tr>
<td>B 117</td>
<td>78</td>
</tr>
<tr>
<td>C 195</td>
<td>78</td>
</tr>
<tr>
<td>D 195</td>
<td>117</td>
</tr>
</tbody>
</table>

3. The activity of a sample containing a radioactive element is 6400 Bq. After 36 minutes the activity is 800 Bq. What is the half-life of the sample?
   - A  4.0 minutes
   - B  8.0 minutes
   - C  12 minutes
   - D  18 minutes

4. A sample contains a small quantity of a radioactive element with a very long half-life. The activity is constant and equal to \(A\). The temperature of the sample is increased. What are the effects if any, on the half-life and activity of the sample?

<table>
<thead>
<tr>
<th>Effect on half-life</th>
<th>Effect on activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>A  none</td>
<td>none</td>
</tr>
<tr>
<td>B  none</td>
<td>increase</td>
</tr>
<tr>
<td>C  increase</td>
<td>none</td>
</tr>
<tr>
<td>D  increase</td>
<td>increase</td>
</tr>
</tbody>
</table>

5. What is the common characteristic of most nuclei with mass number greater than about 20?
   - A  binding energy per nucleon
   - B  binding energy
   - C  decay pattern
   - D  half-life
6 The binding energy per nucleon for $^{11}_B$ is about 7 MeV. What is the minimum energy needed to separate the nucleons of $^{11}_B$?

A 7 MeV  B 35 MeV  C 42 MeV  D 77 MeV

7 The reaction $p + n \rightarrow p + \pi^0$ is impossible. Which conservation law would be violated if the reaction occurred?

A charge  B lepton number  C baryon number  D strangeness

8 Which is the neutral exchange particle of the weak interaction?

A photon  B gluon  C W  D Z

9 What are the charge $Q$ and strangeness $S$ of the baryon $\Lambda = (uds)$?

<table>
<thead>
<tr>
<th></th>
<th>Q</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>+1</td>
</tr>
<tr>
<td>B</td>
<td>+1</td>
<td>+1</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>D</td>
<td>+1</td>
<td>-1</td>
</tr>
</tbody>
</table>

10 What process does this Feynman diagram represent?

A electron emitting photon  B electron absorbing photon  C positron emitting photon  D positron absorbing photon

11 a Explain how the emission lines in the spectrum of a gas are evidence for discrete energy levels within atoms.

The diagram shows three energy levels of a vapour.

Transitions between these three levels give rise to photons of three different wavelengths. Two of these wavelengths are 486 nm and 656 nm.
b On a copy of the diagram draw arrows to identify the transitions that give rise to the wavelengths of 656 nm and 486 nm.

c Calculate the wavelength of the photon that corresponds to the third transition.

d White light containing wavelengths that vary from 400 nm to 700 nm is transmitted through the vapour. On a copy of the diagram below, draw lines to show the absorption lines in the transmitted light.

12 a Explain why in their experiment Geiger and Marsden used:
   i an evacuated enclosure
   ii a gold foil that was very thin
   iii a beam of alpha particles that was very narrow.

b State the name of the force responsible for the deflection of the alpha particles.

c i Describe the deflections of the alpha particles by the gold foil.
   ii Outline how the results of this experiment led to the Rutherford model of the atom.

d The diagram shows a partially completed path of an alpha particle that left point P as it scatters past a nucleus of gold.

On a copy of the diagram:
   i complete the path
   ii draw lines to clearly show the angle of deflection of this alpha particle
   iii draw an arrow to indicate the direction of the force on the alpha particle at the point of closest approach.

e i A second alpha particle is shot at the nucleus from position Q with identical kinetic energy, in a direction parallel to that of the alpha particle at P. On your diagram, draw the path of this particle.
   ii Discuss how, if at all, the answer to e i would change if the nucleus of gold were replaced by a nucleus of another, heavier, isotope of gold.
13  a  Radioactive decay is random and spontaneous. State what you understand by this statement.  [4]

b  The graph shows how activity of a sample containing a radioactive isotope of thorium $^{225}_{90}$Th varies with time.

\[
\begin{array}{|c|c|}
\hline
A/Bq & 8000 \\
\hline
0 & 6000 \\
5 & 4000 \\
10 & 2000 \\
15 & 0 \\
\hline
\end{array}
\]

\[t/\text{min} \quad 0 \quad 5 \quad 10 \quad 15 \quad 20 \quad 25 \quad 30\]

i  State what is meant by an isotope.  [1]

ii  Determine the half-life of thorium.  [2]

iii  State one assumption made in obtaining the answer to ii.  [1]

iv  Draw on a copy of the graph to show the variation of the activity with time to 30 minutes.  [2]

c  i  Thorium undergoes alpha decay. Complete the reaction equation:

\[^{225}_{90}\text{Th} \to ^{221}_{88}\text{Ra} + ^4_2\text{He} \]  [2]

ii  Calculate the energy released, in MeV. (Atomic masses: thorium 226.024903 u, radium 221.013917 u, helium 4.0026603 u.)  [2]

d  The nuclei of thorium are at rest when they decay. Determine the fraction of the energy released that is carried by the alpha particle.  [3]

14  A possible fission reaction is given by the equation:

\[\frac{1}{2}\text{n} + ^{235}_{92}\text{U} \to ^{90}_{38}\text{Sr} + ^{139}_{54}\text{Xe} + x\text{n} \]

a  i  Calculate the number $x$ of neutrons produced.  [1]

ii  Use the binding energy per nucleon curve in Figure 7.12 to estimate the energy released in this reaction.  [3]

b  Suggest why most nuclei with $A > 20$ have roughly the same binding energy per nucleon.  [3]

c  Use the diagram in Figure 7.12 to explain why energy is released in nuclear fusion.  [2]
15 a Explain, in terms of quarks, the difference between a baryon and a meson. [2]

b In a copy of the table below, put a check mark (√) to identify the interaction(s) that apply to hadrons and to leptons. [2]

<table>
<thead>
<tr>
<th></th>
<th>strong</th>
<th>weak</th>
</tr>
</thead>
<tbody>
<tr>
<td>hadrons</td>
<td></td>
<td></td>
</tr>
<tr>
<td>leptons</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

c Copy and complete the Feynman diagram to represent the beta minus decay of a neutron, making sure that you label all particles involved. [5]

d For this part of the question it is given that $K^− = sū, π^+ = u\bar{d}$ and that $Σ^−$ has strangeness $−1$.

i Using the fact that the reaction $K^− + p \rightarrow π^+ + Σ^−$ occurs, determine whether $Σ^−$ would be classified as a baryon or as a meson. [2]

ii Using the fact that the reaction $K^− \rightarrow μ^- + \bar{ν}$ occurs, determine whether the reaction takes place through the strong, the weak or the electromagnetic interaction. [2]

iii State and explain whether the anti-neutrino in d ii is an electron, muon or tau anti-neutrino. [2]

16 A student suggest that the muon decays according to the reaction equation $μ^- \rightarrow e^- + γ$. [2]

a i State one similarity and one difference between the electron and the muon. [2]

ii Explain why the reaction equation proposed by the student is incorrect. [2]

b In fact, the muon decays according to $μ^- \rightarrow e^- + \bar{ν}_e + ν_μ$. A Feynman diagram for this decay is shown. [2]

i Identify the three unlabelled particles in this diagram. [3]

ii Using the diagram above to construct a new Feynman diagram representing the scattering of an electron anti-neutrino off a muon. [2]

iii Write down the reaction equation representing the decay $μ^+$, which is the anti-particle of the $μ^-$. [2]

c The interaction responsible for the decay of the muon has very short range. State the property of the exchange particle that is responsible for the short range. [1]
Conceptual Questions

(These questions are not in an IB style but instead designed to check your understanding of the concept of this topic. You should try your best to appropriately communicate your answer using prose)

1. How do we know there is such a thing as the strong nuclear force? [2 marks]

2. What are the two major limitations of the Rutherford “planetary” model of the atom? [2 marks]

3. What improvement did the Bohr model of the atom make on Rutherford’s model to allow for the explanation of emission spectra? [2 marks]

4. On the periodic table the atomic mass of the elements are usually given to 3 or 4 decimal places. Explain how it is possible to have non-integer values of elements on the table when a nucleus is made of a whole number of protons and neutrons. [1 mark]
Calculation-based Questions

5. What elements are represented by the X in the following:
   (a) $^{232}_{92}X$; (b) $^{18}_{7}X$; (c) $^{1}_{1}X$; (d) $^{82}_{38}X$;  (e) $^{247}_{97}X$

6. For each of the elements in the previous question, state the number of protons and neutrons.
Conceptual Questions
(These questions are not in an IB style but instead designed to check your understanding of the concept of this topic. You should try your best to appropriately communicate your answer using prose)

1. Why are all nuclei above Z=82 unstable? What is it that makes nuclei unstable? [3 marks]

2. Explain why Wolfgang Pauli proposed that a newly undiscovered particle was emitted, along with an electron, during Beta decay. [1 mark]
3. What is the origin of gamma decay and why does it not cause a change in the atomic mass? [2 marks]

Calculation-based Questions

You will need a periodic table to answer these questions. You will not need one in the test.

4. Fill in the missing particle or nucleus:
   a. \( ^{45}_{20}\text{Ca} \rightarrow ? + e^- + \bar{\nu} \)
   b. \( ^{58}_{29}\text{Cu} \rightarrow ? + \gamma \)
   c. \( ^{46}_{24}\text{Cr} \rightarrow ? + ^{46}_{23}\text{V} \)
   d. \( ^{234}_{94}\text{Pu} \rightarrow ? + \alpha \)
   e. \( ^{239}_{93}\text{Np} \rightarrow ? + ^{239}_{94}\text{Pu} \)

5. What element is formed by the radioactive decay of
   a. \( ^{24}_{11}\text{Na} \ (\beta) \)
   b. \( ^{210}_{84}\text{Po} \ (\alpha) \)
   c. \( ^{35}_{16}\text{S} \ (\beta) \)
   d. \( ^{32}_{16}\text{P} \ (\beta) \)
   e. \( ^{211}_{83}\text{Bi} \ (\alpha) \)
Calculation-based Questions

1. A radioactive source has a half-life of 3.00 min. At the start of an experiment there was 32.0 mg of radioactive material present. How much will there be after 18.0 min? [2 marks]

2. The initial activity of a radioactive sample is 120 Bq. If after 24 hr the activity is measured to be 15 Bq, find the half-life of the sample. [1 mark]

3. Beryllium-8 ($^{8}_{3}Be$) decays into two identical particles. What are they? [1 mark]

4. An isotope has a half-life of 20 min. If initially there is 1024 g of this isotope, how much time must go by for there to be 128 g left? [1 mark]

5. The activity of a sample is initially 80 decays per minute. It becomes 5 decays per minute after 4 hr. What is the half-life? [1 mark]

6. The activity of a sample is 15 decays per minute. The half-life is 30 min. When was the activity 60 decays per minute? [1 mark]
Calculation-based Questions

You will need a periodic table to answer these questions. You will not need one in the test.

1. Estimate the total binding energy for (a) $^{40}_{20}Ca$; (b) $^{238}_{92}U$; (c) $^{84}_{36}Kr$. [3 marks]

2. Calculate the binding energy of deuterium ($^2_1H$)

3. Calculate the binding energy per nucleon of a $^{14}_7N$ nucleus.

4. Show that a nucleus $^8_4Be$ (mass = 8.005305u) is unstable and will decay into two alpha particles.
Conceptual Questions

1. Apart from the positron, all the anti-particles of baryons and leptons have obvious names. Not so for mesons! The mesons have baryon number 0 and lepton number 0. Some of them are anti-particles of others, but three of the mesons in these cards are their own anti-particles. Can you identify all these?

2. Use the particle cards to check that the following decay reactions are all possible. The rules are:
   - Mass/energy is conserved. In practice, this means that the mass on the left hand side of the equation must be more than the mass on the right hand side if the reaction is to go.
   - (Electric) charge is conserved
   - Baryon number is conserved
   - Lepton number is conserved
   - Strangeness may be conserved, or may change by 1
   (The symbol γ refers to a gamma photon.)

   \[ K^+ \rightarrow \mu^+ + \nu_\mu \]
   \[ \Lambda \rightarrow p + \pi^- \]
   \[ \Omega^- \rightarrow \Xi^0 + \pi^- \]
   \[ \Sigma^0 \rightarrow \Lambda + \gamma \]
   \[ \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \]
3. Here are some impossible decay reactions. For each one, use the particle cards to find why the reaction is not possible.

\[
\begin{align*}
\text{n} & \rightarrow \text{p} + \text{e}^- + \nu_e \\
\Delta^+ & \rightarrow \pi^+ + \pi^0 \\
\Xi^0 & \rightarrow \text{p} + \pi^0 \\
\Sigma^+ & \rightarrow \text{p} + K^0
\end{align*}
\]
Three quarks for Muster Mark

The American physicist Murray Gell-Mann gave the name ‘quarks’ to the particles he proposed as the basic building bricks of other particles. The name refers to a line in the novel *Finnegans Wake* by James Joyce, who was famed for his word play. The line is: ‘Three quarks for Muster Mark’. His colleague George Zweig wanted to call the particles ‘aces’, but Gell-Mann’s choice won out. In spite of the rhyme suggested by Joyce’s line, the word ‘quark’ is generally pronounced ‘quork’. The word is also German slang for ‘nonsense’ and the trade name for a type of yoghurt!

These questions ask about how quarks go together to make other particles.

Two kinds of quark

The simplest particles, including all the ones that everyday matter is made of, are built from two kinds (‘flavours’) of quark: ‘up’ and ‘down’. The most peculiar thing about them is that their electric charges come in multiples of 1/3 of the charge on an electron. On a scale where the charge on an electron is $-1e$, with $e = 1.6 \times 10^{-19}$ C, the charges on the quarks are:

- Up quark $u$: charge $+\frac{2}{3}e$.
- Down quark $d$: charge $-\frac{1}{3}e$.

Making massive particles

Relatively massive particles like the proton and neutron are made of combinations of three quarks.

1. What is the charge on the combination $uuu$?

2. What is the charge on the combination $uud$?

3. What is the charge on the combination $udd$?

4. What is the charge on the combination $ddd$?
There are four compound particles here.

5. Which combination has the right charge to be a proton?

6. Which combination has the right charge to be a neutron?

7. There is a particle called the $\Delta^-$ which has a charge of $-1e$. Which quark combination could be the $\Delta^-$?

8. There is a particle called the $\Delta^{++}$ which has a charge of $+2e$. Which quark combination could be the $\Delta^{--}$?

9. A neutron can be changed to a proton if one quark changes ‘flavour’. What change is needed? What charge must be carried away if this happens?
Making mesons

Other, lighter 'middle-weight' particles called mesons can be made from pairs of quarks. But they have to be made from a special combination: a quark and an antiquark. There are now four particles to play with:

- Up quark $u$: charge $+\frac{2}{3}$ e
- Down quark $d$: charge $-\frac{1}{3}$ e.
- Antiup quark $\bar{u}$: charge $-\frac{2}{3}$ e.
- Antidown quark $\bar{d}$: charge $+\frac{1}{3}$ e.

10. What is the charge on the combination $u\bar{u}$?

11. What is the charge on the combination $d\bar{d}$?

12. What is the charge on the combination $u\bar{d}$?

13. What is the charge on the combination $d\bar{u}$?

14. Which combination could be the $\pi^+$ meson?

15. Which combination could be the $\pi^-$ meson?

16. Which could be the neutral $\pi^0$ meson?
Conceptual Questions

Here is the equation for the reaction in which a neutron decays to a proton p, an electron e and an antineutrino $\bar{\nu}$:

$$\overset{1}{0}n \rightarrow \overset{1}{1}p + \overset{0}{-1}e + \overset{0}{0}\bar{\nu}.$$ 

1. How does the equation show that the total number of nucleons remains the same?

2. How does the equation show that the total electric charge remains the same?

3. Which symbols show that the electron and antineutrino are not nucleons, but leptons with zero nucleon number?

4. An electron is a lepton. An antineutrino is an antilepton. Explain how in this reaction the lepton number is conserved, even though it creates two leptons.

Here is the equation for an electron interacting with a proton to produce a neutron and a neutrino:

$$\overset{0}{-1}e + \overset{1}{1}p \rightarrow \overset{1}{0}n + \overset{0}{0}\nu.$$ 

5. How does the equation show that the total number of nucleons remains the same?

6. How does the equation show that the total electric charge remains the same?

7. How does the equation show that the total lepton number remains the same? Why is this neutrino not an antineutrino?
The stable iron nucleus is $^{56}_{26}$Fe; ‘lightweight’ iron $^{49}_{26}$Fe decays emitting a positron and a neutrino. ‘Heavyweight’ iron $^{62}_{26}$Fe decays emitting an electron and an antineutrino. Here are the reactions:

8. In the first equation, what values show that the nucleon number stays the same?

9. In the second equation, what values show that the nucleon number stays the same?

10. How can you see from the first equation that charge is conserved?

11. How can you see from the second equation that charge is conserved?

12. In the first equation, the positive electron (positron) is an antilepton. How does the equation show that total lepton number is unchanged even though two are produced?

13. In the second equation, why is an antineutrino emitted?

14. In both equations, how does the reaction change the chemical element involved?
Calculation-based Questions

Using $E_{\text{rest}} = m c^2$

These questions give practice in using $E_{\text{rest}} = m c^2$ to calculate photon energies and masses of particles created or annihilated.

Energy and mass

The energy of a particle at rest is all due to its mass. This energy is called the rest energy. The rest energy in joules of a particle with mass $m$ measured in kilograms is given by

$$E_{\text{rest}} = m c^2,$$

where $c$ is the speed of light in metres per second. An energy in joules can be converted to electron volts by dividing by $1.60 \times 10^{-19}$ J eV$^{-1}$.

The mass of an electron or positron is $9.11 \times 10^{-31}$ kg. The speed of light is $3.00 \times 10^8$ m s$^{-1}$.

1. Show that the rest energy of an electron is $8.2 \times 10^{-14}$ J.

2. Use the answer to question 1 to show that the rest energy of an electron is 0.51 MeV.

3. Write down the rest energy of a positron (antielectron).

4. An electron and a positron which meet annihilate one another. By how much does the rest energy decrease in total? Express the answer in MeV.

5. The annihilation of an electron and a positron at rest produces a pair of identical gamma ray photons travelling in opposite directions. Write down in MeV the energy you expect each photon to have.

6. A single photon passing near a nucleus can create an electron–positron pair. Their rest energy comes from the energy of the photon. Write down the smallest photon energy that can produce one such pair.
7. Cosmic rays can send high-energy photons through the atmosphere. What approximately is the maximum number of electron–positron pairs that a 10 GeV photon can create?

8. The isotope $^{24}\text{Mg}$ is stable. The light isotope $^{22}\text{Mg}$ emits positrons and gamma rays including a photon of energy 1.28 MeV. How can decays of this nucleus result in both annihilation and creation of electron–positron pairs?

9. A photon can create particle–antiparticle pairs of greater mass than electrons and positrons. Approximately what energy must a photon have to create a proton–antiproton pair? (The mass of a proton is 2000 times the mass of an electron).

10. Why do the photons from the annihilation of an electron–positron pair not themselves go on to create new electron–positron pairs?
Topic 7: Atomic, nuclear and particle physics

Topic 7.1 & 7.2: Discrete energy and radioactivity & Nuclear reactions

1. The Geiger-Marsden alpha particle scattering experiment provides evidence for the existence of

   A. atomic nuclei.        B. neutrons.
   C. protons.             D. nuclear energy levels.

2. In the Geiger-Marsden experiment, $\alpha$ particles are scattered by gold nuclei. The experimental results indicate that most $\alpha$ particles are

   A. scattered only at small angles.
   B. scattered only at large angles.
   C. absorbed in the target.
   D. scattered back along the original direction.

3. The atomic line spectra of elements provides evidence for the existence of

   A. photons.
   B. electrons.
   C. quantized energy states within nuclei.
   D. quantized energy states within atoms.

4. Which one of the following correctly gives the number of electrons, protons and neutrons in a neutral atom of the nuclide $^{65}_{29}$Cu?

<table>
<thead>
<tr>
<th>Number of electrons</th>
<th>Number of protons</th>
<th>Number of neutrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. 65</td>
<td>29</td>
<td>36</td>
</tr>
<tr>
<td>B. 36</td>
<td>36</td>
<td>29</td>
</tr>
<tr>
<td>C. 29</td>
<td>29</td>
<td>65</td>
</tr>
<tr>
<td>D. 29</td>
<td>29</td>
<td>36</td>
</tr>
</tbody>
</table>

5. The number of nucleons in a nucleus is the number of

   A. particles in the nucleus.
   B. neutrons in the nucleus.
   C. protons in the nucleus.
   D. protons plus neutrons in the nucleus.
6. Isotopes provide evidence for the existence of
   A. protons.      B. electrons.
   C. nuclei.       D. neutrons.  

7. Ag-102, Ag-103 and Ag-104 are three isotopes of the element silver.
   Which one of the following is a true statement about the nuclei of these isotopes?
   A. All have the same mass.
   B. All have the same number of nucleons.
   C. All have the same number of neutrons.
   D. All have the same number of protons.  

8. Which of the following identifies the significant interaction(s) between nucleons inside the nucleus?
   A. Nuclear only
   B. Coulomb only
   C. Nuclear and Coulomb
   D. Gravitational, nuclear and Coulomb  

9. The nucleus of an atom contains protons. The protons are prevented from flying apart by
   A. the presence of orbiting electrons.
   B. the presence of gravitational forces.
   C. the presence of strong attractive nuclear forces.
   D. the absence of Coulomb repulsive forces at nuclear distances.  

10. The unified mass unit is defined as
    A. the mass of one neutral atom of $^{12}_6$C.
    B. $\frac{1}{12}$ of the mass of one neutral atom of $^{12}_6$C.
    C. $\frac{1}{6}$ of the mass of one neutral atom of $^{12}_6$C.
    D. the mass of the nucleus of $^{12}_6$C.  


11. Which of the following best describes why alpha-particles travel only a short distance in air?

A. They undergo radioactive decay.
B. They undergo elastic collisions with air molecules.
C. They ionize air molecules.
D. They are attracted by the nuclei of air molecules.

12. A nucleus of the isotope potassium-40 \( ^{40}_19 \, K \) decays to form a nucleus argon-40 \( ^{40}_18 \, Ar \). Which one of the following correctly identifies the other two particles resulting from this decay?

A. \( \beta^- \) and \( \nu \)
B. \( \beta^- \) and \( \bar{\nu} \)
C. \( \beta^+ \) and \( \nu \)
D. \( \beta^+ \) and \( \bar{\nu} \)

13. The nucleus \( ^{30}_15 \, P \) undergoes radioactive decay to the nucleus \( ^{30}_14 \, Si \). The particles emitted in the decay are

A. a positron and an antineutrino.
B. an electron and an antineutrino.
C. a positron and a neutrino.
D. an electron and a neutrino.

14. In a laboratory when aluminium nuclei are bombarded with \( \alpha \)-particles, the following reaction may take place.

\[
^4_2 \text{He} + ^{27}_13 \text{Al} \rightarrow ^{30}_15 \text{P} + ^1_0 \text{n}
\]

This reaction is an example of

A. nuclear fission.
B. nuclear fusion.
C. natural radioactive decay.
D. artificial transmutation.
15. K-capture is a process that occurs when a nucleus captures an electron from the innermost shell of electrons surrounding the nucleus.

When K-capture occurs in iron-55 ($^{55}_{26}$ Fe), the nucleus is changed into a manganese (Mn) nucleus. Which equation represents this change?

A. ($^{55}_{26}$ Fe) + $^0_1$ e → $^{55}_{25}$ Mn

B. ($^{55}_{26}$ Fe) + $^1_0$ e → $^{56}_{27}$ Mn

C. ($^{55}_{26}$ Fe) + $^0_{-1}$ e → $^{55}_{25}$ Mn

D. ($^{55}_{26}$ Fe) + $^1_{-1}$ e → $^{56}_{25}$ Mn

16. When the isotope aluminium-27 is bombarded with alpha particles, the following nuclear reaction can take place.

$$^4_2\text{He} + ^{27}_{13}\text{Al} \rightarrow X + \text{neutron}$$

Which of the following correctly gives the atomic (proton) number and mass (nucleon) number of the nucleus $X$?

<table>
<thead>
<tr>
<th>Proton number</th>
<th>Nucleon number</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. 15</td>
<td>30</td>
</tr>
<tr>
<td>B. 16</td>
<td>31</td>
</tr>
<tr>
<td>C. 30</td>
<td>15</td>
</tr>
<tr>
<td>D. 31</td>
<td>16</td>
</tr>
</tbody>
</table>

17. The binding energy per nucleon of the nucleus $^7_3\text{Li}$ is approximately 5 MeV. The total energy required to completely separate the nucleons of this nucleus is approximately

A. 15 MeV.

B. 20 MeV.

C. 35 MeV.

D. 50 MeV.
18. The graph below illustrates the variation with nucleon number (mass number) \( N \) of the binding energy per nucleon \( E \) of nuclei.

Which of the labelled nuclei is the most stable?

![Graph showing binding energy per nucleon]  

19. A freshly-prepared sample of cobalt-64 (\(^{64}\text{Co}\)) decays by the emission of \( \gamma \)-ray photons. The decay may be represented by the nuclear equation

\[ ^{64}_{27}\text{Co} \rightarrow ^{64}_{27}\text{Co} + \text{energy}. \]

After this decay, the binding energy per nucleon has

A. increased in magnitude because energy has been emitted from the nucleus.
B. decreased in magnitude because energy has been emitted from the nucleus.
C. stayed constant because the number of nucleons in the nucleus is unchanged.
D. stayed constant because the proton number is unchanged.

20. Two light nuclei of masses \( m_1 \) and \( m_2 \) fuse in a nuclear reaction to form a nucleus of mass \( M \). Which of the following expressions correctly relates the masses of the nuclei?

A. \( M > m_1 + m_2 \)
B. \( M < m_1 + m_2 \)
C. \( M = m_1 + m_2 \)
D. \( M = m_1 - m_2 \)
21. The equation of a nuclear reaction is shown below.

\[ ^1_1H + ^1_1H \rightarrow ^3_2He + ^1_0n \]

The reaction is an example of

A. artificial transmutation.
B. fission.
C. natural radioactivity.
D. fusion.

22. The graph below shows the variation with mass (nucleon) number of the average binding energy per nucleon.

Which direction indicates a fission reaction with a release of energy?

A. I
B. II
C. III
D. IV

23. The rest-mass of a nucleus of lithium-7 \( ^7_3Li \) is \( m_L \). The rest-mass of a proton is \( m_p \) and the rest-mass of a neutron is \( m_N \). The speed of light in free space is \( c \).

Which of the following is a correct expression for the binding energy of a lithium-7 nucleus?

A. \( (3m_p + 4m_N - m_L)c^2 \)
B. \( (3m_p + 4m_N + m_L)c^2 \)
C. \( (4m_p + 3m_N - m_L)c^2 \)
D. \( (3m_p + 7m_N - m_L)c^2 \)
24. The source of the Sun’s energy is
   A. fission.        B. radioactivity.
   C. fusion.        D. ionization.

25. Radioactive decay is a random process. This means that
   A. a radioactive sample will decay continuously.
   B. some nuclei will decay faster than others.
   C. it cannot be predicted how much energy will be released.
   D. it cannot be predicted when a particular nucleus will decay.

26. A sample of a radioactive isotope of half-life $T_\frac{1}{2}$ initially contains $N$ atoms. Which one of the following gives the number of atoms of this isotope that have decayed after a time $3T_\frac{1}{2}$?
   A. $\frac{1}{8}N$        B. $\frac{1}{3}N$
   C. $\frac{2}{3}N$        D. $\frac{7}{8}N$

27. A nuclide X has a half-life of 10 s. On decay the stable nuclide Y is formed. Initially a sample contains only atoms of X.
   After what time will 87.5% of the atoms in the sample have decayed into nuclide Y.
   A. 9.0 s
   B. 30 s
   C. 70 s
   D. 80 s

28. A sample of material contains 64 $\mu$g of a radioactive isotope. After sixty minutes 2.0 $\mu$g of the isotope remain. The half-life of this isotope is
   A. 10 minutes.
   B. 12 minutes.
   C. 15 minutes.
   D. 20 minutes.
29. This question is about atomic spectra.

An electron undergoes a transition from an atomic energy level of $3.20 \times 10^{-15}$ J to an energy level of $0.32 \times 10^{-15}$ J. Determine the wavelength of the emitted photon.

..............................................................................................................................................
..............................................................................................................................................
..............................................................................................................................................
..............................................................................................................................................
..............................................................................................................................................

(Total 3 marks)

30. This question is about nuclear binding energy.

(a) (i) Define nucleon.

..............................................................................................................................................

(1)

(ii) Define nuclear binding energy of a nucleus.

..............................................................................................................................................
..............................................................................................................................................

(1)

The axes below show values of nucleon number $A$ (horizontal axis) and average binding energy per nucleon $E$ (vertical axis). (Binding energy is taken to be a positive quantity).
(b) Mark on the $E$ axis above, the approximate position of

(i) the isotope $^{56}_{26}$Fe  (label this F).  

(ii) the isotope $^{2}_1$H  (label this H).  

(iii) the isotope $^{238}_{92}$U  (label this U).  

(c) Using the grid in part (a), draw a graph to show the variation with nucleon number $A$ of the average binding energy per nucleon $E$.

(d) Use the following data to deduce that the binding energy per nucleon of the isotope $^{3}_2$He is 2.2 MeV.

- nuclear mass of $^{3}_2$He  = 3.01603 u  
- mass of proton  = 1.00728 u  
- mass of neutron  = 1.00867 u  

(e) (i) State the name of this type of reaction.

(ii) Use your graph in (c) to explain why energy is released in this reaction.

In the nuclear reaction $^2_1$H + $^2_1$H → $^3_2$He + $^1_0$n  energy is released.

(Total 13 marks)
31. This question is about radioactivity and nuclear energy.

(a) Define the following terms,

   (i) **Isotope**

   ...........................................................................................................................
   ...........................................................................................................................

   ...........................................................................................................................

   (1)

   (ii) **Radioactive half-life**

   ...........................................................................................................................
   ...........................................................................................................................

   ...........................................................................................................................

   (1)

Thorium-227 (Th-227) results from the decay of the isotope actinium-227.

(b) (i) Complete the following reaction equation.

\[
^{227}_{89}\text{Ac} \rightarrow ^{227}_{90}\text{Th} + \]

(1)

Th-227 has a half-life of 18 days and undergoes \(\alpha\)-decay to the isotope Ra-223 (Ra-223). A sample of Th-227 has an initial number of 32 arbitrary units.

(ii) Using the axes below, draw a graph to show the variation with time \(t\) (for \(t = 0\) to \(t = 72\) days) of the number of Th-227.

![Graph](image)

(2)

(iii) Determine from your graph, the number of thorium after 50 days.

...........................................................................................................................

(1)
In the decay of a Th-227 nucleus, a \( \gamma \)-ray photon is also emitted.

(c) Use the following data to deduce that the energy of the \( \gamma \)-ray photon is 0.667 MeV.

- mass of Th-227 nucleus = 227.0278 u
- mass of Ra-223 nucleus = 223.0186 u
- mass of helium nucleus = 4.0026 u
- energy of \( \alpha \)-particle emitted = 5.481 MeV
- unified atomic mass unit (u) = 931.5 MeV c\(^{-2}\)

You may assume that the Th-227 nucleus is stationary before decay and that the Ra-223 nucleus has negligible kinetic energy.

....................................................................................................................................
....................................................................................................................................
....................................................................................................................................
....................................................................................................................................
....................................................................................................................................

(3)
(Total 9 marks)

32. Radioactive decay

(a) The nucleon number (mass number) of a stable isotope of argon is 36 and of a radioactive isotope of argon is 39.

(i) State what is meant by a nucleon.
....................................................................................................................................
....................................................................................................................................
....................................................................................................................................
....................................................................................................................................

(1)

(ii) Explain, in terms of the number of nucleons and the forces between them, why argon-36 is stable and argon-39 is radioactive.
....................................................................................................................................
....................................................................................................................................
....................................................................................................................................
....................................................................................................................................
....................................................................................................................................

(4)

(b) A particular nucleus of argon-39 undergoes the decay shown by the nuclear reaction equation below.

\[ _{18}^{39} \text{Ar} \rightarrow _{19}^{39} \text{K} + \beta^- \]

(i) State the proton (atomic) number and the nucleon (mass) number of the potassium (K) nucleus.

Proton number: ............................................................................................................

Nucleon number: ...........................................................................................................
(ii) Use the following data to determine the maximum energy, in J, of the $\beta^-$ particle in the decay of a sample of argon-39.

Mass of argon-39 nucleus = 38.96431 u

Mass of K nucleus = 38.96370 u

(c) The graph below shows the variation with time $t$ of the number of a sample of argon-39.

Use the graph to determine the half-life of argon-39. Explain your reasoning.
1. This question is about deducing the quark structure of a nuclear particle.

When a $K^-$ meson collides with a proton, the following reaction can take place.

$$K^- + p \rightarrow K^0 + K^+ + X$$

$X$ is a particle whose quark structure is to be determined.

The quark structure of mesons is given below.

<table>
<thead>
<tr>
<th>particle</th>
<th>quark structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^-$</td>
<td>$su$</td>
</tr>
<tr>
<td>$K^+$</td>
<td>$us$</td>
</tr>
<tr>
<td>$K^0$</td>
<td>$ds$</td>
</tr>
</tbody>
</table>

(a) State and explain whether the original $K^-$ particle is a hadron, a lepton or an exchange particle.

...........................................................................................................................................................
...........................................................................................................................................................
...........................................................................................................................................................

(2)

(b) State the quark structure of the proton.

...........................................................................................................................................................
...........................................................................................................................................................
...........................................................................................................................................................

(2)

(c) The quark structure of particle X is $sss$. Show that the reaction is consistent with the theory that hadrons are composed of quarks.

...........................................................................................................................................................
...........................................................................................................................................................
...........................................................................................................................................................

(2)

(Total 6 marks)

2. This question is about particle physics.

A neutron can decay into a proton, an electron and an antineutrino according to the reaction

$$n \rightarrow p + e + \bar{\nu}_e.$$
(a) Deduce the value of the electric charge of the antineutrino.

............................................................................................................................................. (1)

(b) State the name of the fundamental interaction (force) that is responsible for this decay.

............................................................................................................................................. (1)

(c) State how an antineutrino differs from a neutrino.

............................................................................................................................................. (1)

(Total 3 marks)

3. This question is about particle physics.

(a) Possible particle reactions are given below. They cannot take place because they violate one or more conservation laws. For each reaction identify one conservation law that is violated.

(i) \( \mu^- \rightarrow e^- + \gamma \)

Conservation law: .................................................... (1)

(ii) \( p + n \rightarrow p + \pi^0 \)

Conservation law: .................................................... (1)

(iii) \( p \rightarrow \pi^+ + \pi^- \)

Conservation law: .................................................... (1)

(b) State the name of the exchange particle(s) involved in the strong interaction.

............................................................................................................................................. (1)

(Total 4 marks)

4. This question is about the decay of a neutron.

The diagram below illustrates a neutron decaying into a proton by emitting a \( \beta^- \)-particle.

\[ \text{proton} \rightarrow \text{proton} + \text{particle X} \]

\[ \text{neutron} \rightarrow \text{proton} + \text{particle Y} \]

\[ \beta^- \text{-particle} \]

62
State the name of

(a) the force involved in this decay;
...................................................................................................................................
(1)

(b) the particle X;
...................................................................................................................................
(1)

(c) the exchange particle Y involved in the decay.
...................................................................................................................................
(1)

(Total 3 marks)

5. This question is about radioactive decay.

The decay process of a neutron is given by the following equation.

\[ n \rightarrow p + \bar{e} + \bar{\nu}_e \]

(a) Complete the table below.

<table>
<thead>
<tr>
<th>particle</th>
<th>( n )</th>
<th>( p )</th>
<th>( e^- )</th>
<th>( \bar{\nu}_e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>baryon number</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>lepton number</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(2)

(b) Baryon number and lepton number are both conserved in this decay process. State one other property that is conserved.
...................................................................................................................................
(1)

(Total 3 marks)
6. This question is about fundamental interactions.

(a) The Feynman diagram below represents a $\beta^-$ decay via the weak interaction process.

The exchange particle in this weak interaction is a virtual particle.

(i) State what is meant by a virtual particle.

..............................................................................................................................................
..............................................................................................................................................
..............................................................................................................................................
..............................................................................................................................................
..............................................................................................................................................
..............................................................................................................................................
..............................................................................................................................................
..............................................................................................................................................

(1)

(ii) Determine whether the virtual particle in the process represented by the Feynman diagram is a $W^+$, a $W^-$ or a $Z^0$ boson.

..............................................................................................................................................
..............................................................................................................................................
..............................................................................................................................................
..............................................................................................................................................
..............................................................................................................................................
..............................................................................................................................................
..............................................................................................................................................
..............................................................................................................................................

(2)
(Total 3 marks)
The radioactive nuclide beryllium-10 (Be-10) undergoes beta minus (\(\beta^–\)) decay to form a stable boron (B) nuclide.

1a. Identify the missing information for this decay. [1 mark]

\[ ^{10}\text{Be} \rightarrow ^{7}\text{B} + \beta + \nu \]

The initial number of nuclei in a pure sample of beryllium-10 is \(N_0\). The graph shows how the number of remaining beryllium nuclei in the sample varies with time.

1b. On the graph, sketch how the number of boron nuclei in the sample varies with time. [2 marks]

1c. After \(4.3 \times 10^6\) years, [3 marks]

\[
\frac{\text{number of produced boron nuclei}}{\text{number of remaining beryllium nuclei}} = 7.
\]

Show that the half-life of beryllium-10 is \(1.4 \times 10^6\) years.
1d. Beryllium-10 is used to investigate ice samples from Antarctica. A sample of ice initially contains $7.6 \times 10^{11}$ atoms of beryllium-10. State the number of remaining beryllium-10 nuclei in the sample after $2.8 \times 10^6$ years.

An ice sample is moved to a laboratory for analysis. The temperature of the sample is $-20$ °C.

1e. State what is meant by thermal radiation.  

1f. Discuss how the frequency of the radiation emitted by a black body can be used to estimate the temperature of the body.

1g. Calculate the peak wavelength in the intensity of the radiation emitted by the ice sample.

Derive the units of intensity in terms of fundamental SI units.
1h. Derive the units of intensity in terms of fundamental SI units. [2 marks]

2a. Rutherford constructed a model of the atom based on the results of the alpha particle scattering experiment. Describe this model. [2 marks]

Rhodium-106 \(^{106}\text{Rh}\) decays into palladium-106 \(^{106}\text{Pd}\) by beta minus \((\beta^-)\) decay. The binding energy per nucleon of rhodium is 8.521 MeV and that of palladium is 8.550 MeV.

2b. State what is meant by the binding energy of a nucleus. [1 mark]

2c. Show that the energy released in the \(\beta^-\) decay of rhodium is about 3 MeV. [1 mark]
\[ \beta^- \text{ decay is described by the following incomplete Feynman diagram.} \]

2d. Draw a labelled arrow to complete the Feynman diagram.  

[1 mark]

2e. Identify particle V.  

[1 mark]

The Feynman diagram shows electron capture.

3a. Deduce that X must be an electron neutrino.  

[2 marks]
3b. Distinguish between hadrons and leptons. [2 marks]

The first scientists to identify alpha particles by a direct method were Rutherford and Royds. They knew that radium-226 (\(^{226}\text{Ra}\)) decays by alpha emission to form a nuclide known as radon (\(^{222}\text{Rn}\)).

4a. Write down the missing values in the nuclear equation for this decay. [1 mark]

\[
^{226}\text{Ra} \rightarrow ^{86}\text{Rn} + 2\alpha
\]

4b. Rutherford and Royds put some pure radium-226 in a small closed cylinder A. Cylinder [1 mark] A is fixed in the centre of a larger closed cylinder B.

\[\text{cylinder A}
\]

\[\text{cylinder B}
\]

At the start of the experiment all the air was removed from cylinder B. The alpha particles combined with electrons as they moved through the wall of cylinder A to form helium gas in cylinder B.

The wall of cylinder A is made from glass. Outline why this glass wall had to be very thin.
4c. Rutherford and Royds expected $2.7 \times 10^{15}$ alpha particles to be emitted during the experiment. The experiment was carried out at a temperature of 18 °C. The volume of cylinder B was $1.3 \times 10^{-5}$ m$^3$ and the volume of cylinder A was negligible. Calculate the pressure of the helium gas that was collected in cylinder B.

4d. Rutherford and Royds identified the helium gas in cylinder B by observing its emission spectrum. Outline, with reference to atomic energy levels, how an emission spectrum is formed.

4e. The work was first reported in a peer-reviewed scientific journal. Outline why Rutherford and Royds chose to publish their work in this way.
5a. A particular K meson has a quark structure $u d$. State the charge on this meson. \[1 \text{ mark}\]

5b. The Feynman diagram shows the changes that occur during beta minus ($\beta^-$) decay. \[2 \text{ marks}\]

\[
\begin{array}{c}
\text{n} \\
\text{u} \rightarrow \text{u} \\
\text{d} \rightarrow \text{d} \\
\text{p} \\
\end{array}
\]

Label the diagram by inserting the **four** missing particle symbols.

5c. Carbon-14 (C-14) is a radioactive isotope which undergoes beta minus ($\beta^-$) decay to the stable isotope nitrogen-14 (N-14). Energy is released during this decay. Explain why the mass of a C-14 nucleus and the mass of a N-14 nucleus are slightly different even though they have the same nucleon number. \[2 \text{ marks}\]

6a. A nucleus of phosphorus-32 ($^{32}_{15}P$) decays by beta minus ($\beta^-$) decay into a nucleus of sulfur-32 ($^{32}_{16}S$). The binding energy per nucleon of $^{32}_{15}P$ is 8.398 MeV and for $^{32}_{16}S$ it is 8.450 MeV.

Determine the energy released in this decay. \[2 \text{ marks}\]
6b. The graph shows the variation with time $t$ of the activity $A$ of a sample containing phosphorus-32 ($^{32}\text{P}_{15}$).

Determine the half-life of $^{32}\text{P}_{15}$.

\[ \text{[1 mark]} \]
6c. Quarks were hypothesized long before their existence was experimentally verified. Discuss the reasons why physicists developed a theory that involved quarks. [3 marks]