The belief in unification

In the early 19th century there were three known forces: gravitational, electric and magnetic. Through the work of James Clerk Maxwell (1831–1879) physicists realised that electric and magnetic forces were two sides of the same force, the electromagnetic force. Thus began the notion (for some a belief, for others a prejudice) that all interactions, as more were being discovered, were part of the same 'unified' force. In the 20th century two new forces were discovered: the weak nuclear force and the strong nuclear force. In the late 1960s the electromagnetic and the weak nuclear force were unified in the standard model of particles. All efforts to unify this electroweak force with the strong nuclear force in a grand unified force have failed. All attempts to unify any of these forces with gravity have also failed. Yet, the dream of unification remains.

Nature of science

Accidental discovery

The discovery of radioactivity is an example of an accidental discovery. Henri Becquerel, working in Paris in 1896, believed that minerals made phosphorescent (emitting light) by visible light might give off X-rays. His idea was to wrap a photographic plate in black paper, and place on it a phosphorescent uranium mineral that had been exposed to bright sunlight. But the sun did not shine, and he stopped the experiment, placing the wrapped plate and the mineral in a drawer. A few days later he developed the photographic plate, expecting to see only a very weak image. To his surprise, there was a very strong image. Becquerel concluded that this image was formed by a new kind of radiation that had nothing to do with light. The radiation came from the uranium mineral. Becquerel conducted further experiments and showed that uranium minerals were the only phosphorescent minerals that had this effect.

Test yourself

1 **a** Discuss what is meant by the statement that the energy of atoms is discrete.
  b Outline the evidence for this discreteness.

2 Explain why the dark lines of an absorption spectrum have the same wavelengths as the bright lines of an emission spectrum for the same element.

3 Calculate the wavelength of the photon emitted in a transition from $n=4$ to $n=2$ in hydrogen. (Use Figure **7.2**.)

4 Refer to Figure **7.1**. Explain why the distance between the emission lines of hydrogen decreases as we move to the right.

5 A hydrogen atom is in its ground state.

a Explain the term **ground state**.

b Photons of energy 10.4 eV are directed at hydrogen gas in its ground state. Suggest what, if anything, will happen to the hydrogen atoms.

c In another experiment, a beam of electrons of energy 10.4 eV are directed at hydrogen gas atoms in their ground state. Suggest what, if anything, will happen to the hydrogen atoms and the electrons in the beam.

6 State the electric charge of the nucleus $^{3}_{2}\text{He}$.

7 a State what is meant by the term **isotope**.

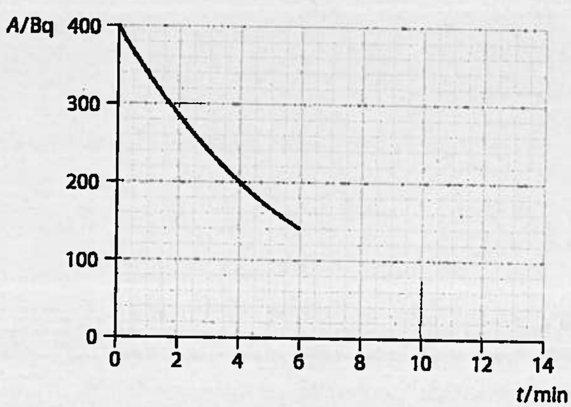
b State **two** ways in which the nuclei of the isotopes $^{16}_{8}\text{O}$ and $^{18}_{8}\text{O}$ differ from each other (other than they have different neutrons).

8 Bismuth ($^{210}_{83}\text{Bi}$) decays by beta minus decay, followed by gamma emission. State the equation for the reaction and the atomic and mass number of the nucleus produced.

9 Plutonium ($^{239}_{94}\text{Pu}$) decays by alpha decay. State the equation for this reaction and name the nucleus plutonium decays into.

10 A radioactive source has a half-life of 3.0 min. At the start of an experiment 32.0 mg of the radioactive material is present. Determine how much will be left after 18.0 min.

11 The graph shows the variation with time of the activity of a radioactive sample.



a State what is meant by **activity**.

b Use the graph to estimate the half-life of the sample.

c On a copy of the graph, extend the curve to show the variation of the activity for a time up to 12 minutes.

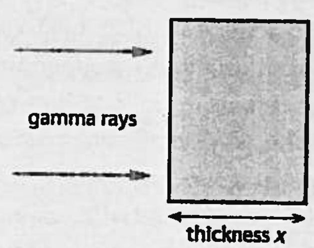
d The sample contains a radioactive element X that decays in to a stable element Y. At $t = 0$ no atoms of element Y are present in the sample. Determine the time after which the ratio of Y atoms to X atoms is 7.

12 In a study of the intensity of gamma rays from a radioactive source it is suspected that the counter rate C at a distance d from the source behaves as $C \propto \left(\frac{1}{d+d_0}\right)^2$ where d_0 is an unknown constant. A set of data for C and d is given. Outline how the data must be plotted in order to get a straight line.

13 The intensity of gamma rays of a specific energy (monochromatic rays) decreases exponentially with the thickness x of the absorbing material according to the equation:

$$I = I_0 e^{-\mu x}$$

where I_0 is the intensity at the face of the absorber and μ a constant depending on the material.



Discuss how the intensity I and thickness x should be plotted in order to allow an accurate determination of the constant μ.

14 State the name of the dominant force between two protons separated by a distance of:

a 1.0×10^{-15} m

b 1.0×10^{-14} m.

15 Large stable nuclei have more neutrons than protons. Explain this observation by reference to the properties of the strong nuclear force.

Test yourself

16 Find the binding energy and binding energy per nucleon of the nucleus $^{62}_{28}Ni$. The atomic mass of nickel is 61.928348 u.

17 How much energy is required to remove one proton from the nucleus of $^{16}_{8}O$? A rough answer to this question is obtained by giving the binding energy per nucleon. A better answer is obtained when we write a reaction that removes a proton from the nucleus. In this case $^{16}_{8}O \rightarrow ^{1}_{1}p + ^{15}_{7}N$. Calculate the energy required for this reaction to take place, known as the proton separation energy. Compare the two energy values. (The atomic mass of oxygen is 15.994 u; that of nitrogen is 15.000 u.)

18 The first excited state of the nucleus of uranium-235 is 0.051 MeV above the ground state.

   a What is the wavelength of the photon emitted when the nucleus makes a transition to the ground state?

   b What part of the spectrum does this photon belong to?

19 Assume uranium-236 splits into two nuclei of palladium-117 (Pd). (The atomic mass of uranium is 236.0455561 u; that of palladium is 116.9178 u.)

   a Write down the reaction.

   b What other particles must be produced?

   c What is the energy released?

20 A fission reaction involving uranium is:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{98}_{40}Zr + ^{135}_{52}Te + 3^{1}_{0}n$$

Calculate the energy released. (Atomic masses: U = 235.043922 u; Zr = 97.91276 u; Te = 134.9165 u.)

21 Calculate the energy released in the fusion reaction:

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n$$

(Atomic masses: $^{2}_{1}H$ = 2.014102 u; $^{3}_{1}H$ = 3.016049 u; $^{4}_{2}He$ = 4.002603 u.)

22 In the first nuclear reaction in a particle accelerator, hydrogen nuclei were accelerated and then allowed to hit nuclei of lithium according to the reaction:

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

Calculate the energy released. (The atomic mass of lithium is 7.016 u.)

23 Show that an alternative formula for the mass defect is $\delta = ZM_H + (A - Z)m_n - M_{atom}$ where M_H is the mass of a hydrogen atom and m_n is the mass of a neutron.

24 Consider the nuclear fusion reaction involving the deuterium ($^{2}_{1}D$) and tritium ($^{3}_{1}T$) isotopes of hydrogen:

$$^{2}_{1}D + ^{3}_{1}T \rightarrow ^{4}_{2}He + ^{1}_{0}n$$

The energy released, Q_1, may be calculated in the usual way, using the masses of the particles involved, from the expression:

$$Q_1 = (M_D + M_T - M_{He} - m_n)c^2$$

Similarly, in the fission reaction of uranium:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{98}_{40}Zr + ^{135}_{52}Te + 3_0n$$

the energy released, Q_2, may be calculated from:

$$Q_2 = (M_U - M_{Zr} - M_{Te} - 2m_n)c^2$$

   a Show that the expression for Q_1 can be rewritten as:

$$Q_1 = E_{He} - (E_D + E_T)$$

   where E_{He}, E_D and E_T are the binding energies of helium, deuterium and tritium, respectively.

   b Show that the expression for Q_2 can be rewritten as:

$$Q_2 = (E_{Zr} + E_{Te}) - E_U$$

   where E_{Zr}, E_{Te} and E_U are the binding energies of zirconium, tellurium and uranium, respectively.

   c Results similar to the results obtained in **a** and **b** apply to all energy-releasing fusion and fission reactions. Use this fact and the binding energy curve in Figure **7.12** to explain carefully why energy is released in fusion and fission reactions.

The Higgs went undetected for about 40 years since its existence was proposed on theoretical grounds. In July 2012 physicists at CERN's Large Hadron Collider announced evidence that finally the Higgs had been discovered. Its mass is about 125 GeV c^{-2}.

Nature of science

At the time Gell-Mann proposed quarks, many hundreds of hadrons were known. Gell-Mann managed to explain the existence of each and every one of these by postulating the existence of just the three lightest quarks (the u, the d and the s). This was a purely mathematical explanation, as no quarks had been observed. Gell-Mann predicted the existence of a 'strangeness −3' baryon and used his quark model to predict its mass as well. In 1964 researchers at Brookhaven discovered the $\Omega-$ with properties exactly as predicted. The bubble chamber photograph in Figure **7.32a** shows the creation and subsequent decay of the $\Omega-$. Analysing these complex photographs and extracting relevant information is an enormously complicated task. Large-scale international collaboration later showed the existence of the other quarks and led to the Standard Model used today. Work on particles continues at CERN in Geneva (Figures **7.32b** and **7.32c**) and many other laboratories.

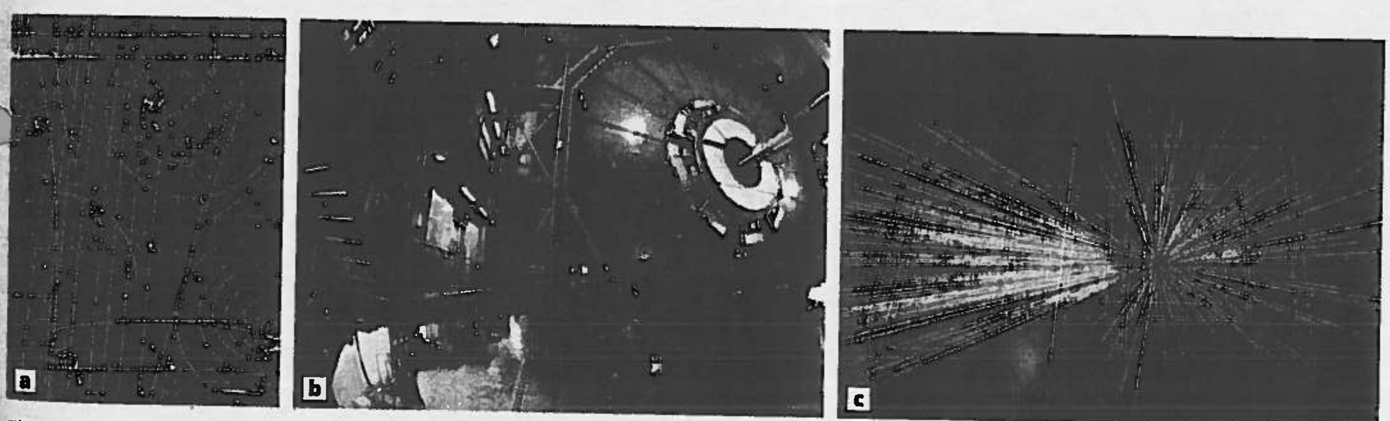


Figure 7.32 **a** A bubble chamber photograph of the creation and decay of the Ω^-. **b** The huge CMS detector at the Large Hadron Collider at CERN illustrates the complexity of the electronics required in particle physics. **c** Computer images of particle tracks after a collision illustrate the complexity of the analysis required.

Test yourself

25 In the gold foil experiment explain why:
  a the foil was very thin
  b the experiment was done in an evacuated container.

26 Write down the quark structure of **a** the anti-neutron and **b** the anti-proton. Verify that the charges come out correctly.

27 Write down the quark structure of the anti-particle of the meson $K^+ = (u\bar{s})$.

28 State the baryon number of the hadron with quark content $\bar{c}\bar{c}\bar{c}$.

29 Determine whether the following reactions conserve or violate baryon number:
  a $p^+ \to e^+ + \gamma$
  b $p^+ + p^- \to \pi^+ + \pi^-$
  c $p^+ + p^- \to \pi^+ + \pi^- + n + \bar{n}$
  d $\Lambda^0 \to \pi^+ + \pi^-$ (The Λ particle has quark content uds.)

30 Suggest the reason that led to the introduction of the quantum number called strangeness.

31 The quark content of a certain meson is ($d\bar{s}$).

a Write down its charge and its strangeness.

b Determine whether it can be its own anti-particle.

32 A charmed D meson is made out of $D = c\bar{d}$.

a Write down its charge.

b Write down its strangeness.

33 Determine whether the following reactions conserve or violate strangeness: (use $\pi^0 = d\bar{d}$, $K^+ = u\bar{s}$, $\Lambda^0 = uds$, $K^0 = d\bar{s}$, $\Sigma^- = dds$)

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

b $p^0 + n \rightarrow K^+ + \Sigma^-$

c $K^0 \rightarrow \pi^- + \pi^+$

d $\pi^- + p^+ \rightarrow \pi^- + \Sigma^+$

34 In the reactions listed below, various neutrinos appear (denoted ν). In each case, identify the correct neutrino (ν_e, ν_μ, ν_τ or the anti-particles of these).

a $\pi^+ \rightarrow p^0 + e^+ + \nu$

b $\pi^+ \rightarrow p^0 + \mu^+ + \nu$

c $\tau^+ \rightarrow \pi^- + \pi^+ + \nu$

d $p^+ + \nu \rightarrow n + e^+$

e $\tau^- \rightarrow e^- + \nu + \nu$

35 The reactions listed below are all impossible because they violate one or more conservation laws. In each case, identify the law that is violated.

a $K^+ \rightarrow \mu^- + \bar{\nu}_\mu + e^+ + e^+$

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

c $\tau^+ \rightarrow \gamma + \bar{\nu}_\tau$

d $p + n \rightarrow p + p^0$

e $e^+ \rightarrow \mu^+ + \bar{\nu}_\mu + \bar{\nu}_e$

f $p \rightarrow \pi^+ + \pi^-$

36 Explain whether the electric force acts:

a on quarks

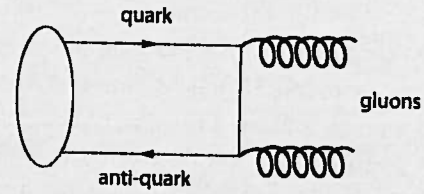
b on neutrinos.

37 The neutron is electrically neutral. Could it possibly have electromagnetic interactions?

38 The neutral meson $\eta_c = (c\bar{c})$ is its own anti-particle, but the neutral $K^0 = (d\bar{s})$ is not. Explain why.

39 a Outline what is meant by the term **confinement** in the context of quarks.

b The Feynman diagram shows the decay of a quark–anti-quark pair in a meson into two gluons. With reference to your answer in **a**, suggest what might happen to the gluons produced in this decay.



40 a The rest mass of the proton is $938\,\text{MeV}\,c^{-2}$ and that of the neutron is $940\,\text{MeV}\,c^{-2}$. Using the known quark contents of the proton and the neutron, calculate the masses of the u and d quarks.

b Using the values you calculated in **a**, predict the mass of the meson π^+ (which is made out of a u quark and an d anti-quark).

c The actual value of the rest mass of the π^+ is about $140\,\text{MeV}\,c^{-2}$. Suggest how this enormous disagreement is resolved.

41 Describe the significance of the Higgs particle in the standard model of quarks and leptons.

42 Use the electromagnetic vertex to draw a Feynman diagram for the scattering of a photon off a positron.

43 Beta-minus decay involves the decay of a neutron into a proton according to the reaction $n \rightarrow p^+ + e^- + \bar{\nu}_e$.

a Describe this decay in terms of quarks.

b Draw a Feynman diagram for the process.

44 Using the basic weak interaction vertex involving a W boson and two quarks or leptons given in Figure **7.28**, draw Feynman diagrams to represent the following processes:

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

b $e^- + \bar{\nu}_e \rightarrow \mu^- + \bar{\nu}_\mu$

c $\pi^+ \rightarrow \mu^+ + \nu_\mu$ (quark structure of positive pion is $u\bar{d}$)

d $K^- \rightarrow \mu^- + \bar{\nu}_\mu$ (quark structure of negative kaon is $s\bar{u}$).

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 $e^- + e^+ \rightarrow \bar{\nu}_\mu + \nu_\mu$
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 $^{60}_{27}Co$ into a nucleus of $^{60}_{28}Ni$ 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 $^{195}_{78}Pt$?

	Number of neutrons	Number of electrons
A	117	195
B	117	78
C	195	78
D	195	117

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?

	Effect on half-life	Effect on activity
A	none	none
B	none	increase
C	increase	none
D	increase	increase

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 $^{11}_{5}B$ is about 7 MeV. What is the minimum energy needed to separate the nucleons of $^{11}_{5}B$?

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

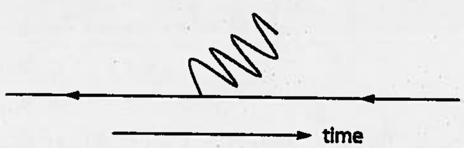
8 Which is the neutral exchange particle of the weak interaction?

A photon　　**B** gluon　　**C** W　　**D** Z

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

	Q	S
A	0	+1
B	+1	+1
C	0	−1
D	+1	−1

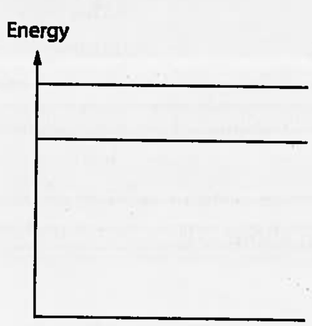
10 What process does this Feynman diagram represent?



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. [3]

The diagram shows three energy levels of a vapour.

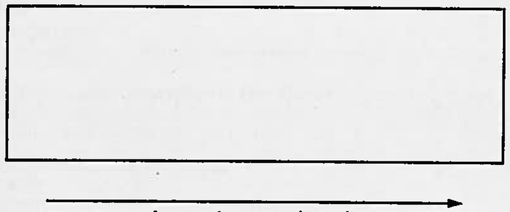


Transitions between these three levels give rise to photons of three different wavelengths. Two of these wavelengths are 486 nm and 656 nm.

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. **[2]**

c Calculate the wavelength of the photon that corresponds to the third transition. **[3]**

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. **[2]**



12 a Explain why in their experiment Geiger and Marsden used:

i an evacuated enclosure **[1]**

ii a gold foil that was very thin **[1]**

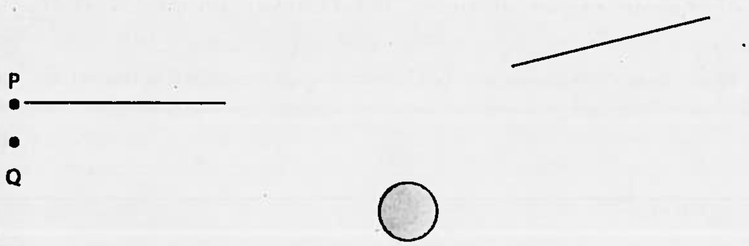
iii a beam of alpha particles that was very narrow. **[1]**

b State the name of the force responsible for the deflection of the alpha particles. **[1]**

c **i** Describe the deflections of the alpha particles by the gold foil. **[2]**

ii Outline how the results of this experiment led to the Rutherford model of the atom. **[3]**

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 **[1]**

ii draw lines to clearly show the angle of deflection of this alpha particle **[2]**

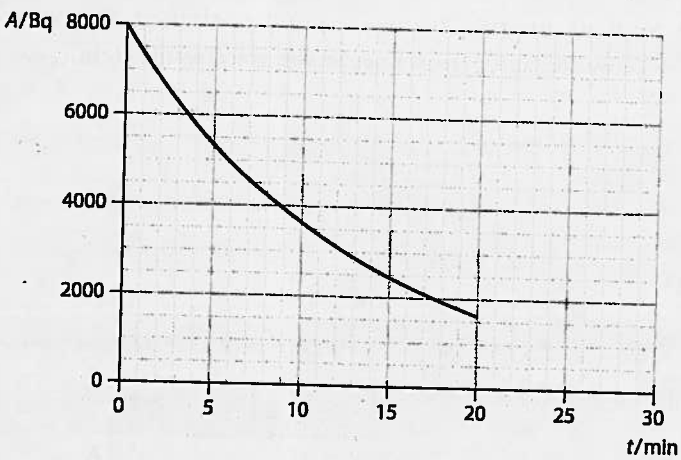
iii draw an arrow to indicate the direction of the force on the alpha particle at the point of closest approach. **[1]**

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. **[2]**

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. **[2]**

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 $^{225}_{90}\text{Th}$ varies with time.



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:

$$^{225}_{90}\text{Th} \rightarrow {}^{?}_{?}\text{Ra} + {}^{?}_{?}\text{a}$$

[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:

$$^{1}_{0}\text{n} + {}^{235}_{92}\text{U} \rightarrow {}^{90}_{38}\text{Sr} + {}^{143}_{54}\text{Xe} + x\,^{1}_{0}\text{n}$$

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]**

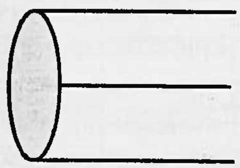
c Use the diagram in Figure **7.12** to explain why energy is released in nuclear fusion. **[2]**

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]**

	strong	weak
hadrons		
leptons		

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 $K^- = s\bar{u}$, $\pi^+ = u\bar{d}$ and that Σ^- has strangeness -1.

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

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

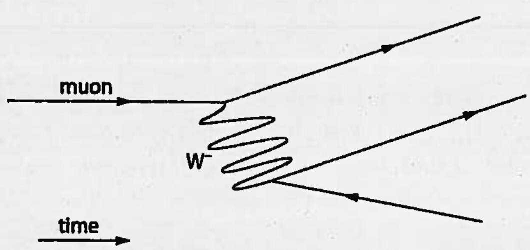
iii State and explain whether the anti-neutrino in **d ii** is an electron, muon or tau anti-neutrino. **[2]**

16 A student suggest that the muon decays according to the reaction equation $\mu^- \rightarrow e^- + \gamma$.

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 $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$. A Feynman diagram for this decay is shown.



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]**