1(a). Technetium−99m ($^{99}_{43}Tc^{m}$) is a metastable radioisotope which can be used as a tracer in medical diagnosis. It is injected into the body and decays by gamma emission into technetium-99 according to the following chemical equation.

$A = \lambda N$

$A = A_0 e^{-\lambda t}$

$$^{99}_{43}Tc^{m} \rightarrow {}^{99}_{43}Tc + {}^{0}_{0}\gamma$$

$N = N_0 e^{-\lambda t}$

i. A technetium-99m tracer with an activity of 900 MBq is injected into a body. The half-life of technetium-99m is 6.01 hours.

Calculate the number of technetium-99m nuclei initially present in the tracer.

$t_{1/2} = 6.01\,h$

$A_0 = 900\ MBq$

$N = ?$ at $t = 0\,s$

$\lambda t_{1/2} = \ln(2) \longrightarrow \lambda = \frac{\ln 2}{6.01 \times 3600} = 3.2 \times 10^{-5}\ 1/s$

$A = \lambda N \longrightarrow N_0 = \frac{A_0}{\lambda} = \frac{900 \times 10^{6}}{3.2 \times 10^{-5}} = 2.8 \times 10^{13}$

number = ... **[3]**

ii. Calculate the time in hours taken for the activity of the tracer to have fallen to 3.0% of its initial activity.

$A = A_0 e^{-\lambda t}$

$\frac{A}{A_0} = e^{-\lambda t} \longrightarrow \ln\left(\frac{A}{A_0}\right) = -\lambda t$

$\frac{A}{A_0} = 0.03$

$\ln(0.03) = -\lambda t \longrightarrow t = \frac{\ln 0.03}{-3.2 \times 10^{-5}} = 109579\ s$

time = ... hours **[3]**

$= 30.4\ h$

(b). The daughter nucleus ($^{99}_{43}Tc$) decays by beta emission with a half-life of a little over 200 000 years. Approximately 50% of it is stored in the bones, and 50% is passed out of the body.

Suggest why the presence of this remaining $^{99}_{43}Tc$ in the body causes little additional risk to the patient.

____

____

____ **[1]**

(c). The half-life of a radioisotope is to be determined using suitable apparatus. Each count represents one decay. The number of counts is measured for one minute every hour over a period of 6 hours. When the data has been collected, a graph of ln(corrected count rate / minute) against time is plotted and shown below.

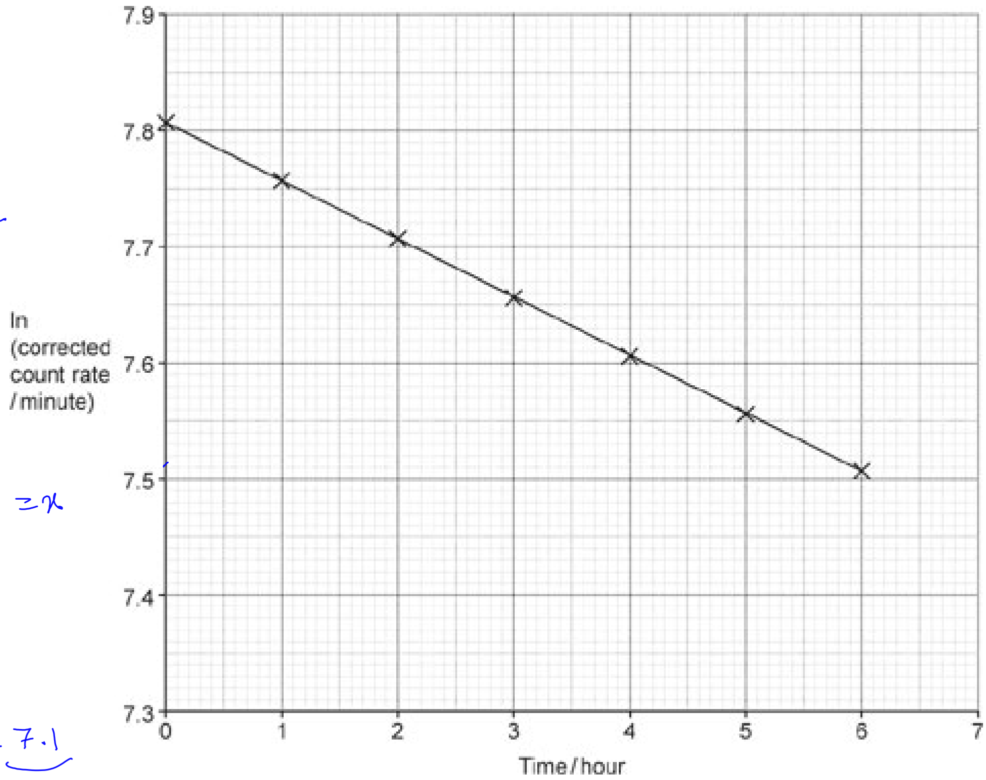
$\ln(x) = 7.8$

$\ln\left(\frac{x}{2}\right) =$

$e^{7.8} = 2440.6 = x$

$\frac{x}{2} = 1220.3$

$\ln(1220.3) = 7.1$



$m = -0.05$

$y = -0.05x + 7.8$

$7.1 =$

$x = \frac{y - 7.8}{-0.05}$

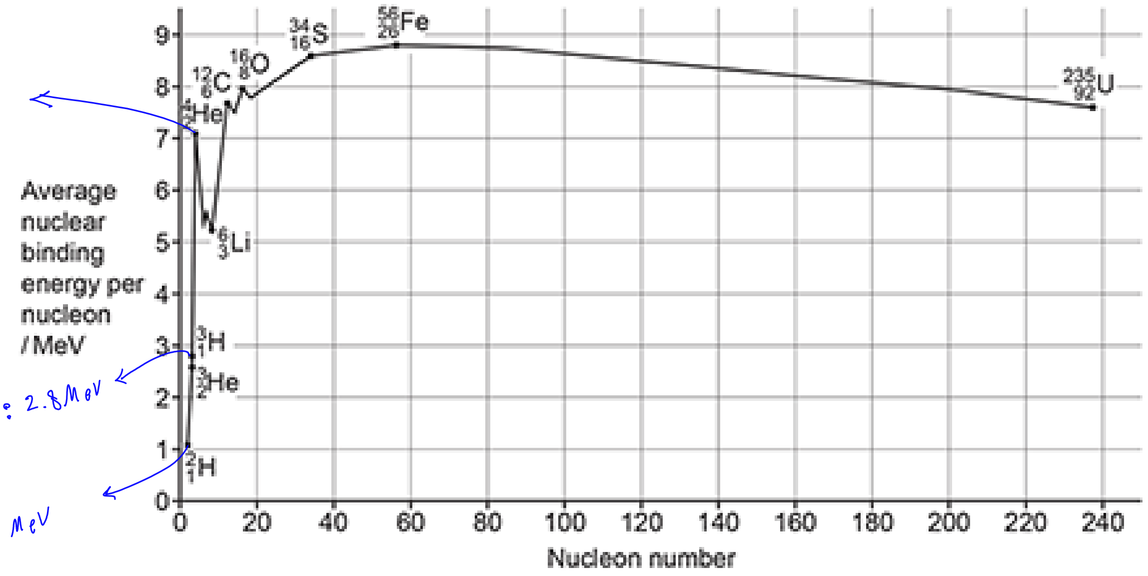
$x = \frac{7.1 - 7.8}{-0.05} = 14$

- Describe an appropriate method that could be used to obtain this data, naming any apparatus and safety precautions taken.
- Use the graph given above to determine the half-life of this radioisotope showing clear working.

- $C = C_0 e^{-\lambda t}$
- $\ln C = \ln C_0 - \lambda t$
- e.g $7.51 = 7.81 - \lambda \times 6$)
- λ around 0.05 hour^{-1}
- $T_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$
- $T_{\frac{1}{2}} = 13.9$ hours (allow any answer that round to 14 hours)
- $T_{\frac{1}{2}} = 830$ minutes or 49 900 seconds (allow some tolerance for slight graph reading discrepancies)
- Or by a graphical method

[6]

2(a). The diagram below shows the average nuclear binding energy per nucleon for a number of different isotopes.



7.1

^3_1H: 2.8 MeV

^2_1H: 1.1 MeV

Explain what is meant by *nuclear binding energy* of a nucleus.

(Minimum) energy required to separate the nucleons

[1]

(b). Suggest why the ^1_1H isotope of hydrogen has **not** been included on the above diagram.

H-1 is a single proton / nucleon AND there is no binding energy / it is not bound to anything

[1]

(c). The main nuclear fusion reaction in the Sun is between nuclei of deuterium (^2_1H) and tritium (^3_1H).

This reaction can be written as shown below.

$$^2_1H + ^3_1H \rightarrow ^4_2He + ^1_0n$$

i. Explain why isotopes with low mass numbers, such as hydrogen, are those which undergo nuclear fusion.

The product has a higher binding energy (per nucleon)

[1]

ii. Use the diagram given at the start of this question to show that, for the reaction of deuterium and tritium, the energy released in each fusion event is approximately 3×10^{-12} J.

$^2_1H : 1.1 = 2 \times 1.1 = 2.2$

$^3_1H : 2.8 = 3 \times 2.8 =$

$-4 \times 7.1 + (2.2 + (3 \times 2.8)) = 18$ MeV **[3]**

$18 \times 10^6 \times 1.6 \times 10^{-19} = 2.8 \times 10^{-12}$ J

iii. The Sun's mass deceases by 4.3 × 10^9 kg every second. Assume that the mass loss is only due to this reaction.

Calculate the number of fusion events per second occurring in the Sun.

$m = \frac{E}{c^2} = \frac{2.8\times10^{-12}}{(3\times10^8)^2} = 3.1\times10^{-29}$ kg

Energy per fusion $= 2.8\times10^{-12}$ J

number of fusion events per second = $\frac{4.3\times10^9}{3.1\times10^{-29}} = 1.38\times10^{38}$ s^{-1} **[2]**

(d). In the Sun, deuterium (^2_1H) is produced from fusion of two hydrogen (^1_1H) nuclei, as shown below. There is a particle missing

Q: +1 +1 → (+1) + (+1) + 0

$$^1_1H + {}^1_1H \rightarrow {}^2_1H + {}^0_1\beta^+ + \nu_e$$

$\bar{\nu}_e$ ν_e

i. Determine the charge of the missing particle.

0 neutral **[1]**

ii. The missing particle is a lepton. Name this lepton.

electron neutrino **[1]**

iii. In the fusion reaction above, determine the total number of up quarks at the **start** of the reaction.

uud + uud ⇒ 4u **[1]**

(e). Tritium ($_1{}^3H$) is another isotope of hydrogen which is formed in stars. On the Earth, tritium is a radioactive element which decays by β emission.

Write down the equation for β- decay in terms of quarks.

$n \rightarrow p + \beta^- + \bar{\nu}_e$

$udd \rightarrow uud + \beta^- + \bar{\nu}_e$ **[2]**

3. This question is about the rate of decay of a radioactive source.

Which of the following statements is/are true?

The rate of decay is

↳ A

$A = A_0 e^{-\lambda t}$ $A = \lambda N$

1 dependent on the decay constant. ✓
2 independent of the mass of the source. ✗ m↑ ⇒ A↑
3 dependent on time. ✓

A 1 only
B 1 and 3 ✓
C 2 only
D 2 and 3

Your answer ☐ **[1]**

4. What is the radius of a carbon nucleus that has 6 protons and 7 neutrons?

$^{A}_{Z}X$

Assume that the average radius of a nucleon r_0 is 1.2 fm.

A 2.2 fm
B 2.3 fm
C 2.8 fm
D 1.6 fm

$R = r_0 \underbrace{A}_{\text{nucleon number}}^{1/3}$ $A = 6+7 = 13$

Your answer ☐ $R = 1.2 \times 10^{-15} \times 13^{1/3} = 2.8\ \text{fm}$ ✓ **[1]**

5. A sub-atomic particle has a positive charge.

Which type of particle is it?

A anti-proton
B down quark
C neutrino
D positron ✓

Your answer ☐ **[1]**

6. A neutrino is a fundamental particle.

Which row of the table correctly describes a neutrino?

	Classification	Force felt
A	hadron	strong nuclear
B	hadron	weak nuclear
C	lepton	strong nuclear
D	lepton	weak nuclear ✓

Your answer ☐ **[1]**

7. Which one of these non-invasive medical scans does **not** expose the patient to ionising radiation?.

A CAT
B PET
C Ultrasound
D X-ray

Your answer ☐ **[1]**

8. A pulsar is a rapidly rotating neutron star that emits radio waves.

A typical neutron star can be modelled as a sphere with mass ≈ 2 × 10^{30} kg and radius ≈ 10 km.

Show that the average density of a neutron star is similar to the average density of an atomic nucleus.

- radius of a nucleon ≈ 1 fm

$\rho = \frac{m}{V}$

$V = \frac{4}{3}\pi r^3 = \frac{4}{3} \times \pi \times (10 \times 10^3)^3 = \ldots$

$\rho = \frac{2 \times 10^{30}}{\ldots} = 4.77 \times 10^{17}$ kg/m^3

nucleus: $m_n = 1.675 \times 10^{-27}$ kg

$\rho = \frac{1.675 \times 10^{-27}}{\frac{4}{3}\pi (1 \times 10^{-15})^3} = 4 \times 10^{17}$ kg/m^3

[3]

9. Large power stations generate an electrical power of about 1 GW.

Current methods of energy production that use nuclear fusion are unable to produce enough energy for large-scale energy production. A proposed method of controlling nuclear fusion is inertial confinement fusion (ICF). ICF uses a large number of powerful lasers to create the high temperatures required for nuclear fusion to occur.

One ICF experiment uses a network of capacitors to store the energy needed to power the lasers. When the network is fully charged:

- potential difference across the network = 24 kV
- total energy stored in the network = 400 MJ

$u = 1.661 \times 10^{-27}$ kg

The fusion reaction in the ICF experiment is

deuterium + tritium → alpha particle + neutron

${}^4_2\alpha$ ${}^2_1H$ ${}^3_1H$

Calculate the number of fusion reactions that must occur for the energy released by fusion to be equal to the electrical energy stored in the network of capacitors.

- mass of deuterium = 2.014102 u
- mass of tritium = 3.016049 u
- mass of alpha particle = 4.002603 u
- mass of neutron = 1.008665 u

mass before $= (2.014102 + 3.016049)$u

" After $= (4.002603 + 1.008665)$u

$\Delta m = 0.018883$ u

$E = \Delta mc^2 = (0.018883 \times 1.661 \times 10^{-27}) \times (3 \times 10^8)^2$

$= 2.82 \times 10^{-12}$ J

No. of fusion $= \frac{400 \times 10^6}{2.82 \times 10^{-12}} = 1.42 \times 10^{20}$

number of fusion reactions = ... **[4]**

10(a). Radiographers commonly use molecules containing fluorine F-18 as tracers in positron emission tomography (PET) scanning.

Fluorine has a proton number of 9.

$p \longrightarrow n + \beta^+ + \nu_e$

F-18 decays to oxygen (O) by β⁺ decay.

Write the equation for the decay of a nucleus of F-18 using nuclear notation.

$${}^{18}_{9}F \longrightarrow {}^{18}_{8}O + {}^{0}_{1}\beta^+ + \nu_e$$

[2]

(b). The β⁺ particle (positron) produced travels only a short distance in the patient before it meets an electron and is annihilated.

$\longrightarrow m \longrightarrow E$

Calculate the wavelength λ of gamma photons produced.

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

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

$E = mc^2 = 9.11 \times 10^{-31} \times (3 \times 10^8)^2 = \ldots$

$\lambda = \frac{hc}{E} = \frac{6.63 \times 10^{-34} \times 3 \times 10^8}{---} = 2.43 \times 10^{-12}$ m

λ = ...m **[3]**

(c). X-rays and gamma-rays are produced by different physical processes.

Briefly describe both processes.

X-ray → electron dropping down in energy levels

γ : Decay of nucleus

[2]

(d). F-18 has a half-life of 109.7 minutes.

Explain the advantage that this has for the patient but the disadvantage that this has for the radiographers.

The half-life is short

Advantage: Exposure of the patient to ionising radiation is kept as low as possible.

Disadvantage: (Radiographers have a) short time to scan/diagnose the patient

[3]

11(a). The energy released from the fusion of 1 kg of hydrogen is more than seven times the energy released by the fission of 1 kg of uranium.

Compare the practicalities of using nuclear fusion of hydrogen with using nuclear fission of uranium to meet our energy needs.

Marks may be awarded for the following considerations only: technology, reaction, fuel, waste, safety.

Technology:
• Fission: technology already established / Fusion:
technology not yet established Reaction:
• Fission: chain reaction self sustaining once initiated
• Fusion: very high temperatures/pressures
/amounts of energy required to initiate and continue reaction / challenges with storage and containment of plasma

Fuel:
• Fission: finite amount of uranium / needs to be enriched • Fusion: (unlimited) fuel available from (sea) water Waste:
• Fission: Produces highly / high level / long half-life / long storage time radioactive waste • Fusion: Produces (effectively)
no radioactive waste (products) / only radioactive **[4]**

(b). Describe how fission of nuclei is induced and controlled in a nuclear reactor.

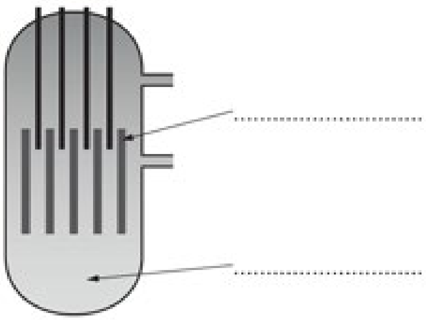
Show how fission leads to the release of large amounts of energy.

The following masses may be useful.

Particle	Mass / u
U-235 nucleus	235.04395
Ba-141 nucleus	140.91440
Kr-92 nucleus	91.92617
${}^{1}_{0}n$ neutron	1.00867

[6]

(c). The diagram shows a simplified layout of a nuclear fission reactor used in a nuclear power station.



Complete the labels on the diagram

[2]

12. Which of these statements is/are true?

1 Antiprotons are hadrons so are subject to the strong nuclear and weak nuclear forces.
2 Neutrons are subject to the weak nuclear force only.
3 The weak nuclear force is the only force that causes a change of quark type.

A 1, 2 and 3
B Only 1 and 2
C Only 1 and 3
D Only 3

Your answer ☐ **[1]**

13(a).

In beta-plus decay, a proton decays into three other particles.

Write a nuclear equation for this process.

[2]

(b). *A student, supervised by their teacher, carries out an experiment with three unlabelled radioactive sources.

The student is told that each source emits only one type of radiation. One emits gamma rays, one emits beta-minus particles and one emits beta-plus particles.

The student has the following equipment:

- a selection of materials with different thicknesses
- a strong magnet
- a radiation counter (GM tube and counter).

Explain how the student can use this equipment to determine safely which radiation each source emits.

You may use the space below to draw a diagram.

[6]

14(a).

Deuterium is an isotope of hydrogen.
A nucleus of deuterium has a proton and a neutron.

Describe the nature and range of the **two** forces acting between these two hadrons.

[4]

(b). *Here is some data for a nucleus of carbon-14 ($^{14}_{6}C$) and a nucleus of uranium-235 ($^{235}_{92}U$).

	Carbon-14 nucleus	Uranium-235 nucleus
Decay mode	Beta-minus decay	Alpha decay
Mass of nucleus / u	14.0	235.0
Radius of nucleus / 10^{-15} m	2.9	7.4

Use the data to:

- describe the composition of the nuclei before and after the decay in terms of hadrons and quarks
- show that both nuclei have the same density.

[6]

15. The mass of a proton is m_p, the mass of a neutron is m_n, and the mass of a hydrogen-3 (^3_1H) nucleus is M. The speed of light in a vacuum is c.
Which expression is correct for the binding energy (B.E.) of the hydrogen-3 nucleus?

A B.E. = $M \times c^2$
B B.E. = $(m_n + m_p - M) \times c^2$
C B.E. = $(m_n + 2m_p - M) \times c^2$
D B.E. = $(2m_n + m_p - M) \times c^2$

Your answer ☐ **[1]**

16. Which of the following statement(s) correctly describe radioactive decay?

1 Radioactive decay can be modelled using dice.
2 Radioactive decay of nuclei is random.
3 Radioactive decay of nuclei is spontaneous

A Only 1
B Only 2
C 2 and 3
D 1, 2 and 3

Your answer ☐ **[1]**

17. A gamma-ray photon of frequency 6.76×10^{22} Hz creates a particle-antiparticle pair. The particle-antiparticle pair have zero kinetic energy.

What is the mass of the particle?

A 2.49×10^{-28} kg
B 4.98×10^{-28} kg
C 7.47×10^{-20} kg
D 4.48×10^{-11} kg

Your answer **[1]**

18. The half-life of fluorine-18 isotope is T.
After time $t = 4T$ the number of fluorine-18 nuclei in a source is N.

How many fluorine-18 nuclei have decayed in the time interval from $t = 0$ to $t = 4T$?

A 3 N
B 4 N
C 15 N
D 16 N

Your answer **[1]**

19. The activity of an alpha-emitting source is 120 kBq. The kinetic energy of each alpha-particle is 4.0 MeV.

What is the rate of energy released by the source?

A 6.4×10^{-13} W
B 4.8×10^{-8} W
C 7.7×10^{-8} W
D 1.2×10^{5} W

Your answer **[1]**

END OF QUESTION PAPER