M1.(a) $^{239}_{93}\text{Np} \rightarrow {}^{239}_{94}\text{Pu} + {}^{(0)}_{(-1)}\beta^- + {}^{(0)}_{(0)}\bar{\nu}$ ✓✓

First mark for one anti-neutrino or one beta minus particle in any form e.g. e^-. If subscript and superscripts are given for these they must be correct but ignore the type of neutrino if indicated.
The second mark is for both particles and the rest of the equation.
Ignore the full sequence if it is shown but the Np to Pu must be given separately for the mark.

2

(b) (i) $T_{1/2}$ 2.0 → 2.1 × 10^5 s ✓
then substitute and calculate
$\lambda = \ln 2 / T_{1/2}$ ✓

$T_{1/2}$ may be determined from graph not starting at zero time.
Look for the correct power of 10 in the half-life – possible AE.

Or
(substitute two points from the graph into $A = A_o e^{-\lambda t}$)
e.g. $0.77 \times 10^{12} = 4.25 \times 10^{12} \exp(-\lambda \times 5 \times 10^5)$ ✓
then make λ the subject and calculate ✓
(the rearrangement looks like
$\lambda = [\ln (A_o / A)] / t$
or $\lambda = -[\ln (A / A_o)] / t$)

Allow the rare alternative of using the time constant of the decay
$A = A_o \exp(-t / t_{tc})$
from graph t_{tc} = 2.9→3.1 × 10^5 s ✓
$\lambda = 1 / t_{tc} = 3.4 \times 10^{-6}\ s^{-1}$ ✓
No CE is allowed within this question.

both alternatives give
λ = 3.3 → 3.5 × 10^{-6} s^{-1} ✓

For reference
$T_{1/2} = 2.0 \times 10^5$ s gives
$\lambda = 3.5 \times 10^{-6}\ s^{-1}$ and
$T_{1/2} = 2.1 \times 10^5$ s gives
$\lambda = 3.3 \times 10^{-6}\ s^{-1}$.

2

(ii) (using $A = N\lambda$
$N = 0.77 \times 10^{12} / 3.4 \times 10^{-6} = 2.2(6) \times 10^{17}$)

allow 2.2 → 2.4 × 10^{17} nuclei ✓

A possible route is find $N_o = A_o / \lambda$

then use $N = N_o e^{-\lambda t}$.

Condone lone answer.

1

(c) (i) uranium (– 235 captures) a neutron (and splits into 2 smaller nuclei / fission fragments) releasing more neutrons ✓

First mark for uranium + neutron gives more neutrons.

Ignore which isotope of uranium is used.

(at least one of) these neutrons go on to cause further / more splitting / fissioning (of uranium– 235) ✓

Second mark for released neutron causes more fission. The word 'reaction□ may replace 'fission□ here provided 'fission / splitting of uranium□ is given somewhere in the answer.

2

(ii) **Escalate if clip shows critical mass in the question.**
the moderator slows down / reduces the kinetic energy of neutrons ✓
so neutrons are absorbed / react / fission (efficiently) by the uranium / fuel ✓

owtte
***Possible escalation**.*

2

(iii) neutrons are absorbed / collide with (by the nuclei in the shielding) ✓

Second mark is only given if neutrons appear somewhere in the answer.

converting the nuclei / atoms (of the shielding) into unstable isotopes (owtte)

No neutrons = no marks.

Making it neutron rich implies making them unstable.

2

[11]

M2.(a) the amount of energy required to separate a nucleus ✓
into its separate neutrons and protons / nucleons ✓
(or energy released on formation of a nucleus ✓

from its separate neutrons and protons / constituents ✓)

1st mark is for correct energy flow direction

2nd mark is for binding or separating nucleons (nucleus is in the question but a reference to an atom will lose the mark)

ignore discussion of SNF etc

both marks are independent

2

(b) (i) $2\,^{1}_{0}\mathrm{n}$ or $^{1}_{0}\mathrm{n} + {}^{1}_{0}\mathrm{n}$ ✓

must see subscript and superscripts

1

(ii) binding energy of U
= 235 × 7.59 ✓ (= 1784 (MeV))
binding energy of Tc and In
= 112 × 8.36 + 122 × 8.51 ✓
(= 1975 (MeV))
energy released (= 1975 – 1784) = 191 (MeV) ✓ (allow 190 MeV)

1st mark is for 235 × 7.59 seen anywhere
2nd mark for 112 × 8.36 + 122 × 8.51 or 1975 is only given if there are no other terms or conversions added to the equation (ignore which way round the subtraction is positioned)
correct final answer can score 3 marks

3

(iii) energy released
= 191 × 1.60 × 10^{-13} ✓
(= 3.06 × 10^{-11} J)
loss of mass (= E / c^2)
= 2.91 × 10^{-11} / (3.00 × 10^{8})^2)
= 3.4 × 10^{-28} (kg) ✓
or
= 191 / 931.5 u ✓ (= 0.205 u)
= 0.205 × 1.66 × 10^{-27} (kg)
= 3.4 × 10^{-28} (kg) ✓

allow CE from (ii)
working must be shown for a CE otherwise full marks can be given for correct answer only

note for CE
answer = (ii) × 1.78 × 10^{-30}

(2.01 × 10^{-27} is a common answer)

2

(c) (i) line or band from origin, starting at 45° up to Z approximately = 20 reading $Z = 80$, $N = 110 \rightarrow 130$ ✓

initial gradient should be about 1 (ie Z = 20 ; N = 15 → 25) and overall must show some concave curvature. (Ignore slight waviness in the line)
if band is shown take middle as the line
if line stops at N > 70 extrapolate line to N = 80 for marking

1

(ii) fission fragments are (likely) to be above / to the left of the line of stability ✓

fission fragments are (likely) to have a larger N / Z ratio than stable nuclei
or
fission fragments are neutron rich owtte ✓
and become neutron or β^- emitters ✓

ignore any reference to α emission
a candidate must make a choice for the first two marks
stating that there are more neutrons than protons is not enough for a mark
1st mark reference to graph
2nd mark – high N / Z ratio or neutron rich
3rd mark beta minus
note not just beta

3
[12]

M3. (a) $({}^{206}_{76}\mathrm{X} \rightarrow {}^{206}_{82}Pb + \beta \times {}^{0}_{-1}\beta + \beta \times \overline{v_e})$

$\beta = 6$ ✓

1

(b) (i) the energy **required** to split up the nucleus ✓

into its individual neutrons and protons/nucleons ✓

(or the energy **released** to form/hold the nucleus ✓

from its individual neutrons and protons/nucleons ✓)

2

(ii) 7.88 × 206 = 1620 MeV ✓ (allow 1600-1640 MeV)

1

(c) (i) U, a graph starting at 3×10^{22} showing exponential fall passing through

0.75×10^{22} near 9×10^{9} years ✓

Pb, inverted graph of the above so that the graphs cross at 1.5×10^{22} near 4.5×10^{9} years ✓

2

(ii) (*u* represents the number of uranium atoms then)

$$\frac{u}{3 \times 10^{22} - u} = 2$$

$u = 6 \times 10^{22} - 2u$ ✓

$u = 2 \times 10^{22}$ atoms

1

(iii) (use of $N = N_o e^{-\lambda t}$)

$2 \times 10^{22} = 3 \times 10^{22} \times e^{-\lambda t}$ ✓

$t = \ln 1.5 / \lambda$

(use of $\lambda = \ln 2 / t_{1/2}$)

$\lambda = \ln 2 / 4.5 \times 10^{9} = 1.54 \times 10^{-10}$ ✓

$t = 2.6 \times 10^{9}$ years ✓ (or 2.7×10^{9} years)

3

[10]

M4. (a) graph passes through N = 10/11 when Z = 10 and N increases as Z increases **(1)**
N = 115 → 125 when Z = 80 and graph must bend upwards **(1)**

2

(b) (i) **W** at $Z > 60$ just (within one diagonal of a square) below line **(1)**

(ii) **X** just (within one diagonal of a square) above line **(1)**

(iii) **Y** just (within one diagonal of a square) below line **(1)**

3

(c) working showing the change due to emission of four α particles **(1)**
four β^- particles **(1)**

1

(d) Any **two** from the following list of processes:

β^+
describe the changes to *N* (up by 1) and *Z* (down by 1)
[or allow p change to n]

α
move closer to line of stability
[or state the proton to neutron ratio is reduced]

p
only if nuclide is **very** proton rich
[or electrostatic repulsion has to overcome the strong nuclear force]
[or highly unstable]
[or rare process]

e^- capture
describe the changes to *N* (up by 1) and *Z* (down by 1)
allow p changes to n

marking: listing **two** processes **(1)**
discussing **each** of the two processes **(1)** **(1)**

3
QWC 1

[10]

M5.(a) (i) alpha **(1)**

(ii) two different track lengths **(1)** short range particles have lower energy than long range particles **(1)**

particles in each range have same energy **(1)**

(4)

(b) (i) $^{239}_{94}\text{Pu} \rightarrow\ ^{235}_{92}\text{U} + \alpha$ **(1)** $(+Q)$

(ii) $^{235}_{92}\text{U} \rightarrow\ ^{231}_{90}\text{Th} + \alpha$ **(1)** $(+Q)$

(iii) U-235 **(1)**

because of the inverse relationship

between half-life and alpha particle energy **(1)**

(iv) because the Th-90 nucleus is neutron-rich compared

with U-235 [or Pu-239] **(1)**

(5)

[9]