7.1 Discrete Energy & Radioactivity

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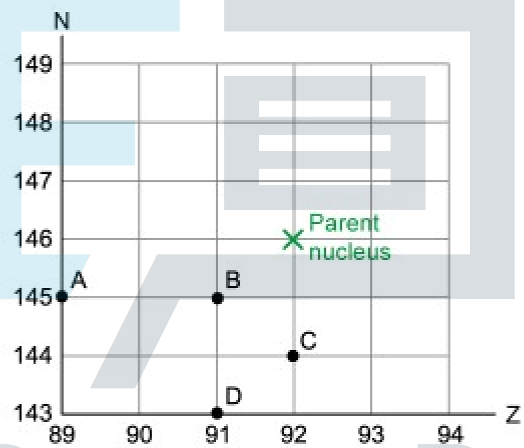
Course	DP IB Physics
Section	7. Atomic, Nuclear & Particle Physics
Topic	7.1 Discrete Energy & Radioactivity
Difficulty	Medium

To be used by all students preparing for DP IB Physics SL
Students of other boards may also find this useful

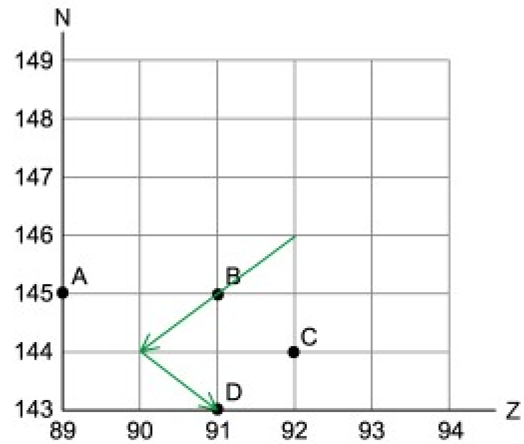
1

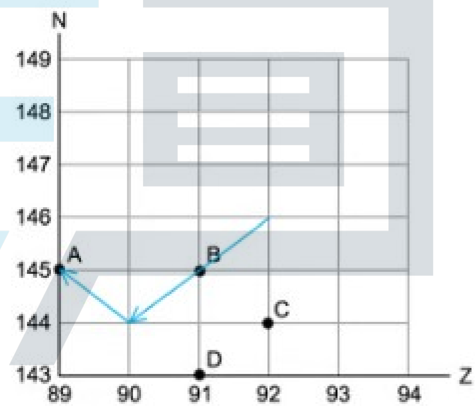
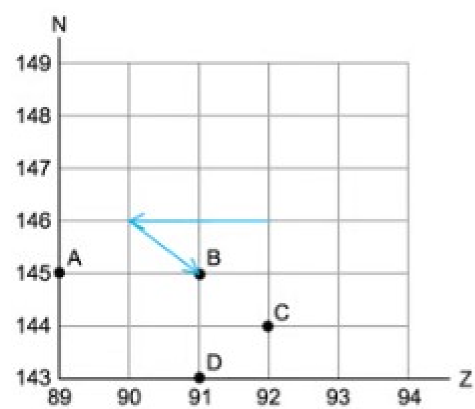
The correct answer is **D** because:

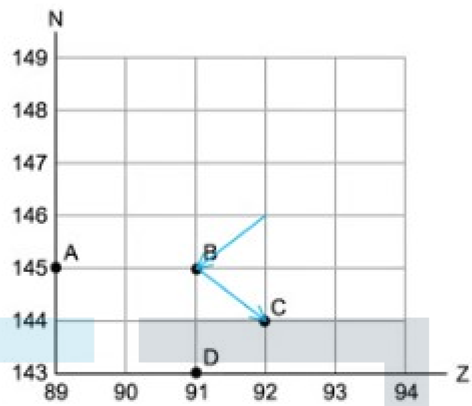
- $^{238}_{92}U$ means that the uranium nucleus contains 92 protons and 146 neutrons
  - The number of neutrons is calculated by subtracting the atomic number from the nucleon number
  - Neutron number = 238 – 92 = 146
- We can then plot the position of uranium-238 (parent nucleus) on the N-Z graph



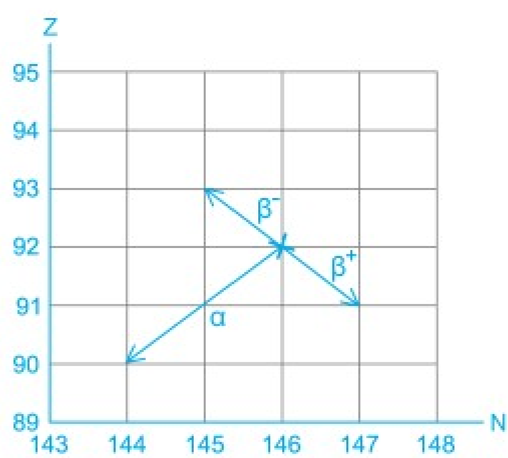
- When a nucleus undergoes alpha decay, an alpha particle is emitted
  - An alpha particle consists of two neutrons and two protons and can be written as $^{4}_{2}\alpha$
- The N and Z values of the nucleus both decrease by two
  - **Note:** Gamma radiation does not affect the number of nucleons
- Beta radiation decreases neutron number by one but increases proton number by one
  - A beta particle is an electron and can be written as $^{0}_{-1}\beta$



A is incorrect as	this represents alpha decay followed by positron, or β^+, decay 
B is incorrect as	this represents alpha decay which neglects to decrease the number of neutrons, followed by beta decay 

C is incorrect as	this would be obtained if the proton and neutron numbers were to only decrease by one during the alpha decay. This is then followed by a beta decay 

To be able to answer these questions correctly, you need to recall that alpha decay is the emission of two neutrons and two protons (a helium-4 nucleus) and that beta decay involves a neutron changing into a proton. This is a diagonal right on the diagram above, but watch out – the axes may not always be this way round! It's better to understand what's going on in each decay as opposed to memorising the paths on an N-Z graph.



Alternatively, you could write out an equation to determine the N and Z values and then find the correct point on the graph

$$^{238}_{92}U \xrightarrow{^{4}_{2}\alpha} {}^{234}_{90}Th \xrightarrow{^{0}_{-1}\beta} {}^{234}_{91}Pa$$

So protactinium, or $^{234}_{91}Pa$ (don't worry, you wouldn't be expected to know its symbol) contains 91 protons and 234 – 91 = 143 neutrons. So, N = 143 and Z = 91

2

The correct answer is **B** because:

- The 80 g sample of living tissue has an activity of 20 Bq
  - Therefore, 20 g of living tissue has an activity of 5 Bq
- After one half-life, the activity is 2.5 Bq
- After two half-lives, the activity is 1.25 Bq – this is the activity of the ancient sample
- The age of the sample is, therefore, equal to two half-lives:
  - 2 × 6000 years = 12 000 years

A is incorrect as	this answer is obtained by halving the half-life as opposed to doubling it
C is incorrect as	this answer is three half-lives instead of two
D is incorrect as	this answer has not accounted for the fact that the living sample is **four** times larger in mass. This means that four half-lives have been calculated instead of two

Any living sample of this tissue will have an activity of roughly 0.25 Bq per gram. This is because the carbon-14 atoms are constantly being replaced by new nuclei from the elephant's diet. Once the organism has died, those nuclei are no longer being replaced and the activity begins to decrease as nuclei decay.

The trick in this question is to spot that the mass of the living sample is four times larger than the mass of the ancient sample. You have to correct this!

If 80 g of living tissue has an activity of 20 Bq, 20g of living tissue has an activity of 5 Bq. Mass of a material and its activity are **directly proportional**.

This activity of 5 Bq has halved twice to give the ancient activity of 1.25 Bq, so two half-lives must have passed since the elephant was last alive.

3

The correct answer is **A** because:

- Since fluorine-18 is a positron emitter, we would expect to see a positron, or beta-plus particle $_{+1}^{0}\beta$, on the right-hand side of the decay equation
  - This eliminates option **B**
- In order to conserve lepton number, the positron must be accompanied by an electron neutrino, υ_e
  - This eliminates option **D**
- The atomic number decreases but the nucleon number remains the same, as a proton changes into a neutron during this process
  - Therefore, we would expect the total nucleon and proton numbers on both sides of the decay equation to be the same
- This is shown by option **A**

$$_{9}^{18}F \rightarrow {}_{8}^{18}O + {}_{+1}^{0}\beta + \upsilon_e$$

Nucleon number: 18 = 18 + 0 + 0 ✓**conserved**

Proton number: 9 = 8 + 1 + 0 ✓**conserved**

B is incorrect as	a beta-minus particle (an electron) is emitted whereas the question refers to a positron i.e. beta-plus decay
C is incorrect as	the atomic number of the nucleus does not change. All other aspects are correct but the atomic number of oxygen does not reflect the fact that a proton has changed into a neutron

D is incorrect as	the neutrino emitted in beta-plus decay should be an electron neutrino. **D** shows an antineutrino being emitted. This does not conserve lepton number

Being aware of the changes that occur in the nucleus during beta-plus and beta-minus decay is crucial to spotting mistakes in atomic number in decay equations.

These decay equations also link closely to the topic on particle conservation laws.

Checking whether lepton number is conserved is a very helpful method for double-checking your answer when it comes to beta decay, as neutrinos or antineutrinos must be emitted alongside the beta particles

$$^{18}_{9}F \rightarrow {}^{18}_{8}O + {}^{0}_{+1}\beta + \upsilon_e$$

When considering just the nuclei, the left side of option **A** has a lepton number of zero. A positron has a lepton number of -1 as it is an antiparticle, so it must be accompanied by a neutrino with a lepton number of +1 to ensure that lepton number is conserved.

4

The correct answer is **D** because:

- When an alpha decay occurs, the following process takes place:
  - $^{231}_{91}Pa \rightarrow {}^{227}_{89}Ac + {}^{4}_{2}\alpha$
- Protactinium-231 will decay to become Actinium-227 (**Note:** you don't need to know the name of these elements) and an alpha particle
  - An alpha particle contains 4 nucleons and 2 protons (effectively a helium-4 nucleus)

- Following the alpha decay, the Actinium-227 will further decay through beta-minus decay:
  - $^{227}_{89}Ac \rightarrow ^{227}_{90}Th + ^{0}_{-1}\beta + \overline{v}_e$
- Actinium-227 will decay to become Thorium-227, an electron (a beta-minus particle) and an antineutrino
- Therefore, the final answer is 90 protons and 227 nucleons
  - $^{231}_{91}Pa \rightarrow A + ^{4}_{2}\alpha \rightarrow B + ^{0}_{-1}\beta^{-} + \overline{v}_e$
- Alternatively, you can calculate the nucleon number of **B** as follows:
  - 231 – 4 – 0 = 227
- And the proton number of **B** as follows:
  - 91 – 2 – (-1) = 90

A is incorrect as	the nucleon number has only reduced by two, whereas four nucleons are emitted during alpha decay. This indicates that the neutrons have been neglected in the alpha decay step. Additionally, the increase in atomic number caused by beta decay has not been accounted for
B is incorrect as	the same misconception about alpha decay from option **A** is present, but this time there is a subsequent increase in atomic number as a result of beta-minus decay has been included
C is incorrect as	the reduction in nucleon number is correct, but the increase in atomic number due to a neutron becoming a proton in beta-minus decay has not been included

If you are not very confident in your understanding of multi-step decays, it is useful to write out each step of the decay so you don't miss anything! It is important to know that alpha particles contain four nucleons, two of which are protons, allowing you to write the first step correctly:

$$^{231}_{91}Pa \rightarrow ^{227}_{89}Ac + ^{4}_{2}\alpha$$

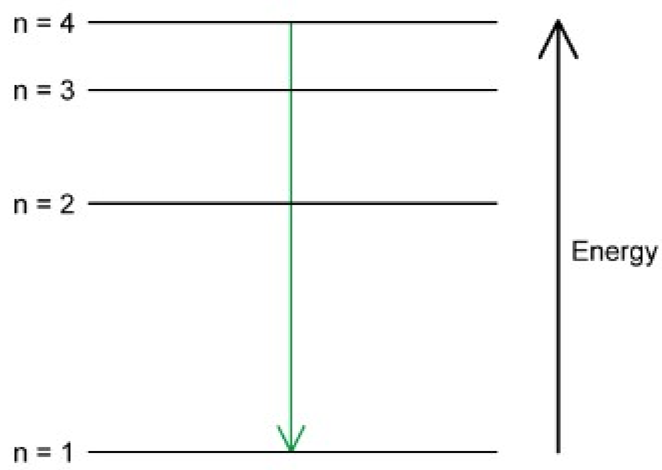
After this step, it is once again important to be aware of the changes within the nucleus during beta decay: a neutron changes into a proton – this is because the nucleus was unstable due to an excess of neutrons. This change is shown by increasing the atomic number but keeping the nucleon number the same.

Once you are more confident with multi-step decays, you can quickly determine new nucleon and proton numbers with a quick calculation, as shown at the end of the worked solution.

5

The correct answer is **A** because:

- The wavelength of each emitted photon is linked to a discrete energy change according to the following equation:
  - $\Delta E = \frac{hc}{\lambda}$
- The electron transition with the largest energy change corresponds to the shortest wavelength of the emitted photon
  - If the overall value of the fraction (ΔE) is larger, the denominator of the fraction (λ) must be small
- The transition between n = 4 and n = 1 gives the largest energy change which corresponds to the shortest wavelength



B is incorrect as	this is the largest transition between consecutive energy levels, but transitions across multiple energy levels are possible, and several of these have a larger energy difference than the transition from n = 2 to n = 1
C is incorrect as	not only is this transition the smallest energy difference, but n = 3 to n = 4 is an excitation process. This involves the absorption of a photon, not the emission of one
D is incorrect as	this transition has the smallest energy change, which would result in the emission of a photon with the largest wavelength of all the transitions shown

Confusion in questions like these can often arise from assuming that a large energy means a large wavelength. It is often helpful to consider more familiar forms of electromagnetic radiation to remind yourself of the inverse proportionality between energy and wavelength.

Remember:

- Gamma rays transfer a **large** amount of energy, and they have a **very short** wavelength
- Radio waves transfer a **small** amount of energy, and they have the **longest** wavelength

6

The correct answer is **C** because:

- Beta radiation has a relatively high ionising power
  - This means that it has a short range in air – typically only a few metres
  - This eliminates options **B** and **D**
- At a range of more than 1.5 m, the count rate is still not zero as background radiation is always present
  - This eliminates option **A**

A is incorrect as	the count rate drops to zero after a certain distance – this cannot happen as there will always be a count rate from the background radiation
B is incorrect as	the count rate in this graph decreases very little with a metre distance – beta radiation only has a range of a few metres to the count rate should reduce a lot at a distance of 1.5 m, this graph is likely to represent gamma radiation
D is incorrect as	the count rate in this graph decreases to the background rate at a distance of only a few centimetres – this graph is likely to represent alpha radiation

It is important that you are aware of the different ranges of the three types of ionising radiation – alpha, beta and gamma:

- Alpha's range is short because it is highly ionising – the particles ionise molecules in the air before they can travel very far
- Beta's range is slightly longer as the particles are less ionising and are moving faster
- Gamma radiation is a form of electromagnetic radiation – this interacts very little with molecules in the air and has the longest range

7

The correct answer is **C** because:

- After every half-life passes, the number of radioactive nuclei remaining also halves
- If 10% of the sample is unstable at the start of the experiment, once the percentage reduces to 2.5%, this means two half-lives have passed

- Similarly, the initial count rate is 180 cpm
- After two half-lives, the count rate will be 45 cpm
  - 180 cpm → 90 cpm represents 1 half life
  - 90 cpm → 45 cpm represents 1 half life

In questions like these, you have to be aware that after every half-life, the amount of radioactive material remaining **halves**. Students can fall into the trap of thinking that a set percentage of radioactive material is **subtracted** after every half-life, but this is incorrect.

You needed to spot that the half-life of the unstable nuclide was 2 hours and then determine the count rate after 4 hours i.e. two half-lives.

It is also worth noting that the number of unstable nuclei, the activity, count rate and mass of a radioactive substance **all** halve after each half-life. This is because they are all directly proportional.

8

The correct answer is **D** because:

- The source is an alpha emitter because:
  - There is a large reduction in count rate when paper is used as a shield
  - Alpha radiation is the only form of ionising radiation that cannot penetrate paper
- The source is **not** a beta emitter because:
  - Beta radiation can penetrate paper but it cannot penetrate aluminium

- While there is a slight reduction in count rate between when a paper shield is replaced with an aluminium shield, 4 cpm (counts per minute) is insignificant and is most likely due to natural fluctuations in background radiation
- The source is a gamma emitter because:
  - Even with aluminium in front of the source, the count rate is 524 cpm
  - Gamma radiation is the only form of ionising radiation that can penetrate aluminium
  - Additionally, the count rate is only reduced when thick lead blocks the source and the intensity of gamma radiation is reduced when passing through thick dense material
- Therefore, the source emits both α and γ radiation

A is incorrect as	there is little difference in count rate between a paper shield and an aluminium shield, implying that beta radiation is not being emitted
B is incorrect as	radiation is still making it through to the Geiger counter even with a paper tube – the source must be emitting more than just alpha radiation
C is incorrect as	the source is an alpha emitter as the count rate reduces with a paper shield and alpha radiation is not included in this answer

It is worth noting that the background count rate naturally fluctuates a little, so we cannot attribute small changes in count rate to the radiation from the source.

9

The correct answer is **B** because:

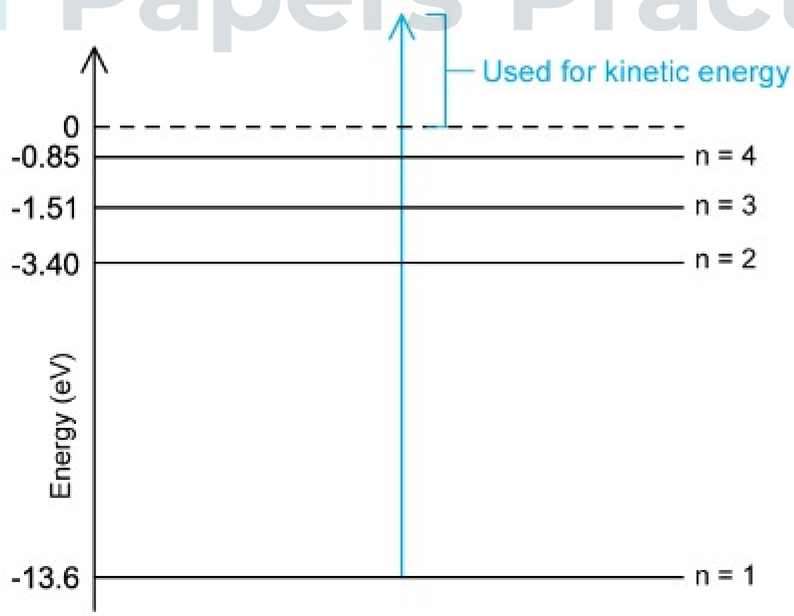
- The difference between the higher energy levels is 3.40 – 0.85 = 2.55, so the energies given must represent a transition from the lowest energy level, n = 1
- No transition from n = 1 has an energy difference of exactly 12.29 eV

- In addition, 12.29 eV is less than 13.6 eV, so it is not a large enough energy to completely ionise the electron
    - Therefore, this photon would **not** be absorbed

A is incorrect as	this is the exact energy difference between n = 1 to n = 2, 13.6 – 3.4 = 10.2 eV, so this photon **will** cause an excitation
C is incorrect as	this is the exact energy difference between n = 1 and n = 4, 13.6 – 0.85 = 12.75 eV, so this photon **will** cause an excitation
D is incorrect as	15 eV may not match a specific transition, but since it is more than 13.6 eV, this energy is enough to cause complete ionisation of the electron

An atom will only absorb a photon if it has exactly the right energy to match a transition between discrete energy levels.

The only exception to this is **ionisation**. If a photon's energy is equal to or more than an atom's ionisation energy (13.6 eV in this case), an electron will be completely removed. Any excess energy from the photon will result in the electron having kinetic energy.



10

The correct answer is **D** because:

- Isotopes of the same element always have the same atomic number – the number of protons
  - Atomic number = nucleon number – neutron number
- **A**, **B** and **C** all have an atomic number of 92
- Whereas option **D**:
  - Atomic number = 239 – 146 = 93
- **D** is the only nucleus with an atomic number of 93, so it is a different element from the other nuclei

A is incorrect as	atomic number = 233 – 141 = 92
B is incorrect as	atomic number = 235 – 143 = 92
C is incorrect as	atomic number = 238 – 146 = 92

For questions like this one, you must be aware that when nuclei have the same number of protons (atomic number), they are the same element by definition. The neutron number may be different, but these are just isotopes of the same element.