7 Read the passage and answer the questions that follow.

Zircon ($ZrSiO_4$) crystals found in rocks serve as reliable timekeepers for determining the age of geological formations. These crystals readily incorporate uranium atoms into their crystal lattice during formation but strongly exclude lead. As a result, any lead found in a zircon crystal can be assumed to be the product of radioactive decay, making the crystal an effective record of the time that has passed since it solidified.

Two uranium decay chains are used in zircon dating: uranium-238 (U-238) decaying to lead-206 (Pb- 206), and uranium-235 (U-235) decaying to lead-207 (Pb-207). These decay processes follow predictable rates, governed by their half-lives: 4.47 billion years for U-238 and 704 million years for U-235. By measuring the ratio of lead to uranium isotopes in a zircon, geologists can determine its age, and thus the age of the rock in which it was found.

The age of a sample of zircon can be derived from the radioactive decay equation and the measured ratio of the lead to uranium isotopes $\dfrac{D}{N}$. For each parent isotope, the number of daughter atoms D accumulated over time is given by:

$$D = N_0 - N$$

where N_0 is the initial number of the parent atom and N is the number of remaining parent atoms.

When both decay systems (U-238 to Pb-206 and U-235 to Pb-207) are measured in a single zircon sample, the results can be plotted on a Concordia diagram—a graph of the isotopic ratios $\dfrac{\text{Pb-206}}{\text{U-238}}$ against $\dfrac{\text{Pb-207}}{\text{U-235}}$. The curve on this graph, known as the Concordia curve, represents points where both decay systems yield the same age, as shown in Fig. 7.1.
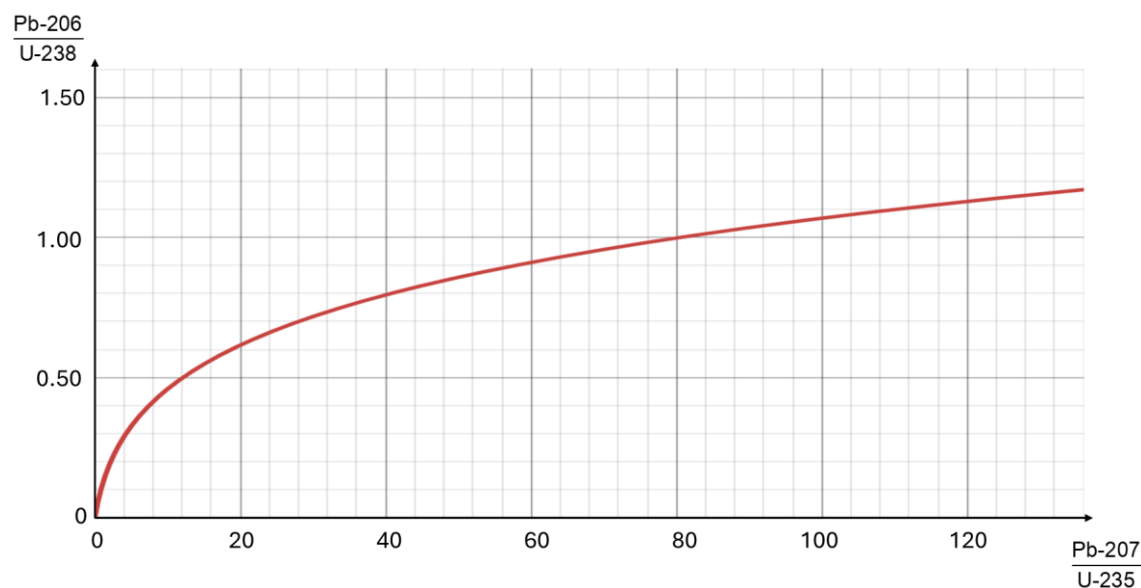

Fig. 7.1

A zircon that has remained isolated from chemical changes since its formation will have ratios of isotopes that lie on this curve, and its age can be confidently determined. If the sample has been altered by natural processes, the resulting isotopic ratios will not be on the curve, indicating that further analysis is required.

To determine these isotopic ratios, geologists use a technique called Secondary Ion Mass Spectrometry (SIMS). In SIMS, a focused primary ion beam (typically O^- or Cs^+) bombards the zircon crystal, releasing atoms from its surface. Some of these atoms are ionised, forming secondary ions that include the uranium and lead isotopes of interest. These ions are then accelerated through a potential difference of 10 kV, gaining kinetic energy as they do so.

After acceleration, the ions enter a uniform magnetic field of 0.75 T that is perpendicular to their velocity. The magnetic force causes the ions to move in circular arcs, with their radius determined by their mass-to-charge ratio. The mass spectrometer thus separates the ions by isotope, as ions like $^{206}Pb^+$ and $^{238}U^+$ follow different trajectories and strike the detector at different positions. The relative intensities of the ion signals are used to calculate the isotopic ratios. Fig. 7.2 below shows the path of the ions in a mass spectrometer.
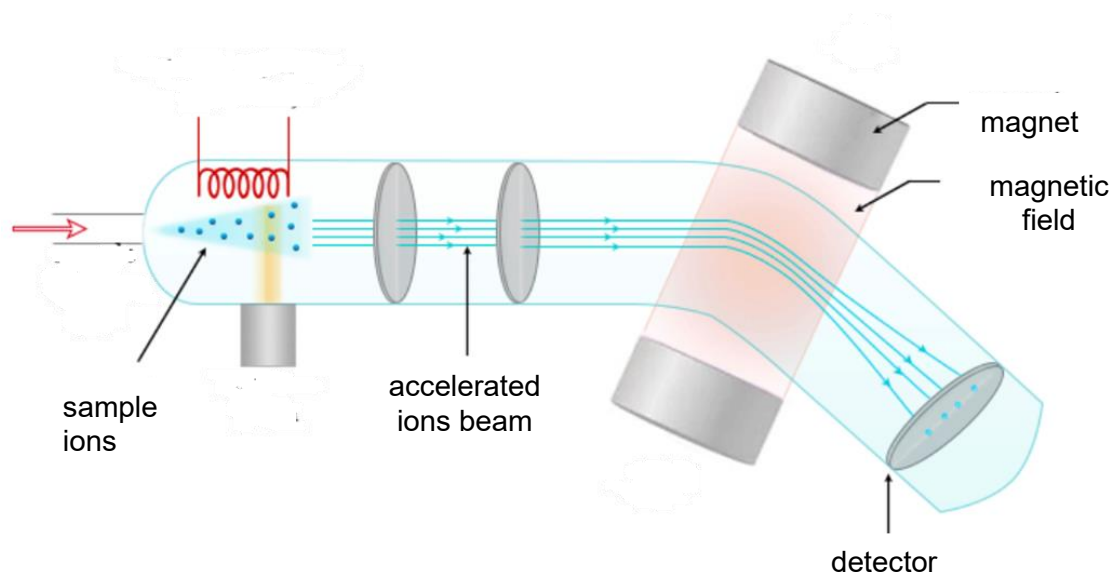

Fig. 7.2

SIMS allows highly precise measurement of isotope ratios in microscopic regions within a single zircon grain. By comparing these measured ratios with those expected from known decay rates and plotting the results on the Concordia diagram, geologists can derive robust and accurate age estimates—often within a few million years—even for samples that are over 4 billion years old.

(a) Explain, using the ratio of daughter to parent nuclei, why isotopes with long half-lives are more suitable than those with short half-lives for dating very old geological samples.

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…….

..……………………………………………………………………………………………………… [1]

(b) Uranium-238 decays into stable lead-206 via a series of alpha and beta decays.

(i) In the first step of the uranium-238 decay chain, a uranium-238 nucleus undergoes alpha decay to form a thorium-234 nucleus and an alpha particle.

The atomic masses of the nuclei involved are:

Mass of uranium-238 nucleus = 238.0508 u
Mass of thorium-234 nucleus = 234.0436 u
Mass of helium-4 nucleus = 4.0026 u

Calculate the energy released in this decay in MeV.

energy released = ………………… MeV   [4]

(ii) Calculate the total number of alpha and beta decays in the decay chain of uranium-238 ($^{238}_{92}U$) to lead-206 ($^{206}_{82}Pb$).

number of alpha decays = ………………

number of beta decays = ………………   [3]

[Turn over

(c) **(i)** Using the radioactive decay equation and the information in the passage, show that the age of a sample of zircon t with a ratio of daughter to parent isotopes $\dfrac{D}{N}$ is given by

$$t = \frac{1}{\lambda}\ln\left(\frac{D}{N} + 1\right)$$

where λ is the decay constant of the parent isotope.

[2]

(ii) In a particular sample of zircon found in Western Australia, the ratio of lead-206 to uranium-238 isotope was found to be 0.978.

Determine the age of the zircon sample t in years.

t = ………………….. years [2]

(iii) The ratio of lead-207 to uranium-235 ratio for the same sample was measured to be 76.0. Using the Concordia diagram (Fig 7.1), determine whether the two ratios agree on the age of this zircon sample.

....

....

.... [2]

(iv) Natural processes may change the number of lead or uranium nuclei in a sample. Suggest what changes may have occurred to the number of nuclei in a certain sample for it to have a data point that lies below the Concordia curve.

....

.... [1]

(d) (i) The ions from a zircon crystal in a SIMS device are accelerated through a potential difference of *V* before entering a uniform magnetic field of magnetic flux density *B* where they move in a circular arc of radius *r*.

Show that the mass to charge ratio of the ions $\frac{m}{q}$ is given by

$$\frac{m}{q} = \frac{B^2 r^2}{2V}$$

[3]

[Turn over

(ii) For the SIMS described in the passage, determine the expected arc radius r for a singly charged $^{206}Pb^+$ ion.

The mass of a $^{206}Pb^+$ ion is 205.974 u.

$r =$ .... m   [2]

(iii) State and explain whether the arc radius of the singly charged $^{238}U^+$ ion will be larger or smaller than that of the lead ion from **(d)(ii)**.

....

....   [2]

[Total: 22]