25.6 Radioactive dating

Specification reference: 6.4.3

Carbon-dating

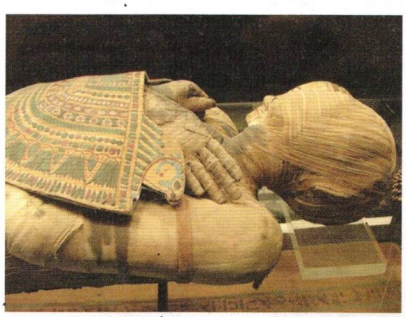
All living things on the Earth contain carbon atoms. Through photosynthesis plants absorb carbon dioxide from the atmosphere, with all the isotopes of carbon, and incorporate these isotopes into their tissues – animals eat the plants, or eat other animals that have eaten the plants, and therefore take in the carbon.

Atmospheric carbon is mainly the stable isotope, carbon-12, but also a tiny amount of the radioactive isotope carbon-14. Carbon-14 has a half-life of about 5700 years and is produced continuously in the upper atmosphere by cosmic rays. The ratio of carbon-14 to carbon-12 nuclei in atmospheric carbon is almost constant at 1.3×10^{-12}. The ratio is the same in all living things. Once an organism dies, it stops taking in carbon, whilst the total amount of carbon-14 it contains continues to decay, so this ratio decreases over time. The activity from carbon-14 in a sample of organic material is proportional to the number of undecayed carbon-14 nuclei. The time since the organism died can therefore be determined by comparing the activities, or the ratios of carbon-14 to carbon-12 nuclei, of the dead material and similar living material. **Carbon-dating** of organic materials as old as 50 000 years is possible with samples as small as nanograms using mass spectrometry.

Learning outcomes

Demonstrate knowledge, understanding, and application of:

→ radioactive dating, such as carbon-dating.



▲ **Figure 1** *Carbon-dating can be used on the wrappings of this Egyptian mummy to find its age*

Atmospheric carbon-14

High-speed protons in cosmic rays from space colliding with atoms in the upper atmosphere produce neutrons. These neutrons in turn collide with nitrogen-14 nuclei in the atmosphere to form carbon-14 nuclei. The carbon-14 nuclei eventually emit beta-minus particles (electrons) and become nitrogen-14 again, so the amount of nitrogen-14 in the atmosphere is replenished.

$$ {}^{1}_{0}\mathrm{n} + {}^{14}_{7}\mathrm{N} \rightarrow {}^{14}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{p} $$

$$ {}^{14}_{6}\mathrm{C} \xrightarrow{\text{half-life} = 5700\ \text{y}} {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\mathrm{e} + \overline{\nu}_{\mathrm{e}} $$

Worked example: Dead wood

A wooden axe found in an Egyptian tomb is found to have an activity of 0.38 Bq. The activity of an identical mass of wood cut from a living tree is 0.65 Bq. Calculate the age of the wood used to make the axe.

Step 1: Calculate the decay constant λ of the isotope of carbon-12. Remember to change the half-life into seconds.

$$\lambda = \frac{\ln(2)}{t_{\frac{1}{2}}} = \frac{\ln(2)}{5700 \times 3.16 \times 10^{7}} = 3.848 \times 10^{-12}\,\text{s}^{-1}$$

Step 2: Use the equation $A = A_0 e^{-\lambda t}$ for activity to determine the age t of the wood.

$$0.38 = 0.65\,e^{-(3.848 \times 10^{-12})t} \quad \text{or} \quad \frac{0.38}{0.65} = e^{-(3.848 \times 10^{-12})t}$$

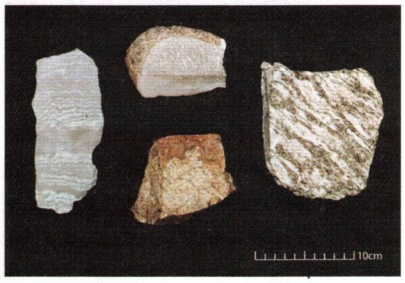
Take natural logarithms (ln) of both sides.

$$\ln\left(\frac{0.38}{0.65}\right) = -3.848 \times 10^{-12} \times t \qquad \text{(remember, } \ln(e^{-x}) = -x\text{)}$$

$$t = \frac{\ln\left(\frac{0.38}{0.65}\right)}{-3.848 \times 10^{-12}} = 1.395\ldots \times 10^{11}\,\text{s} \text{ so age} = 4400 \text{ years (2 s.f.)}$$

Limitations to carbon-dating

There are several limitations to the technique of carbon-dating. It assumes that the ratio of carbon-14 atoms to carbon-12 atoms has remained constant over time. Increased emission of carbon dioxide due to burning fossil fuels may have reduced this ratio, as would natural events such as volcanic eruptions. The ratio may also be affected by solar flares from the Sun and by the testing of nuclear bombs. The tiny amounts of carbon-14 present in organisms also means that the activities are extremely small, about 15 counts per minute for 1 g of carbon – comparable to the background count rate.



▲ **Figure 2** *These are some of the oldest rocks on Earth, dated at 3.7–3.8 billion years old*

Dating rocks

You cannot use carbon-14 to date rocks on the Earth or meteors formed during the creation of the Solar System, because its half-life is not long enough for these ages. Instead, geologists use the decay of rubidium-87 to date ancient rocks. Nuclei of rubidium-87 emit beta-minus particles and transform into stable nuclei of strontium-87. The half-life of the isotope rubidium-87 is about 49 billion years, so it is a good candidate for dating ancient rocks – Earth has been dated to about 4.5 billion years old and the Universe is about 13.7 billion years old.

Summary questions

1 State why carbon-14 is found in all living organisms. *(1 mark)*

2 State how atmospheric carbon-14 is produced in the Earth's atmosphere. *(2 marks)*

3 All living organisms contain the isotope carbon-14.

a Use the information provided in this topic to estimate the activity of 1.0 kg of a living tree due to the decay of carbon-14. *(2 marks)*

b Explain why dating an ancient wooden axe by measuring its activity may be problematic. *(1 mark)*

4 A living wood is found to have an activity of 1.5 Bq. Calculate the activity of a dead wood that is 2000 years old and has the same mass as the living sample. *(3 marks)*

5 A tool made of wood and found in a cave is analysed. The concentration of carbon-14 atoms in this wood is determined using a mass spectrometer. The amount of carbon-14 in the wood is 69% of that in the same mass of wood from a living tree. Estimate the age in years of the dead wood in the tool. *(4 marks)*

6 In some rocks from Scotland, 0.56% of the rubidium-87 originally present is found to have decayed since the rocks were formed. Calculate the age in years of these rocks. *(4 marks)*