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Carbon – 14 Dating

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Content

Abstract

All carbon atoms have 6 protons in their nuclei, but nuclei can also contain 6, 7, or 8 neutrons. There are 3 naturally occurring carbon isotopes on Earth: Carbon-12: Stable core (99% of total natural carbon), Carbon-13: Stabilizes the core (1%), Carbon-14: Unstable radioactive isotope (1 in 1012 carbon atoms in the atmosphere is C-14).

Radioactive isotope of carbon, Discovered by Martin kamen and Samu Ruben ,Naturally occuring isotope , Natural source of carbon 14 on earth and is cosmic ray action on nitrogen in atmosphere.

Radiocarbon dating is a method that provides objective age estimates for carbon-based materials that originated from living organisms. An age could be estimated by measuring the amount of carbon-14 present in the sample and comparing this against an internationally used reference standard.

Carbon-14 is a radioactive isotope of carbon. It comprises about 1.1% of all carbon atoms on earthCarbon-14 has a half-life of 5770 years.

Carbon-14 decays into Nitrogen-14 (which will escape), Through the process of feeding and metabolism, organisms will reach equilibrium with their environment.

In other words, living organisms will maintain a content of about 1.1% carbon-14, Once they die, they will no longer maintain that equilibrium, and C-14 will start turning into N-14.

Introduction

It is a form of radiometric dating, also known as radiocarbon dating or carbon-14 dating ,Carbon-14 dating is one way to do this Determining the age of organic materials based on the decay of unstable substances Isotope carbon 14, and indicates the radioactive isotope of carbon , The radioactive isotope carbon is composed of 6 protons and 8 neutrons ,Carbon 14 can give us up to 40,000 years of history . [W. F. Libby, Radiocarbon Dating, 2nd ed., Univ. of Chicago Press, Chicago, Ill., 1955.]

Radiocarbon (carbon 14) is an isotope of the element carbon that is unstable and weakly radioactive. Stable isotopes are carbon 12 and carbon 13 The invention of radiocarbon dating cleverly combined chemistry and physics to develop a scientific method that can accurately determine the age of organic materials up to about 60,000 years. [R. F. Flint and E. S. Deevey, Jr., (Eds.), American Journal of Science, Radiocarbon Sup-plement, Vol. I (1959),]

It is based on the fact that living organisms (such as trees, plants, humans, and animals) absorb carbon-14 into their tissues. When they die, the carbon-14 begins to transform into other atoms over time. Scientists can estimate when an organism died by counting the remaining carbon-14 atoms. The technique was developed in the late 1940s by University of Chicago chemistry professor Willard Libby, who later won a Nobel Prize for this work. [R. F. Flint and E. S. Deevey, Jr., (Eds.), American Journal of Science, Radiocarbon Sup-plement, Vol. I (1959),]

History of ideas

First developed in the late 1940s at the University of Chicago by Willard Libby, he was a professor of chemistry at the university of Chicago ,He was inspired by physicist Serge Korff , the technique is based on the decay of the carbon-14 isotope.

He determined the half life to be 5568 years ‡ 30 years and it is popularly known as libby half life , this half life has later been re-determined by Godwin as 5730 ‡ 40 years which is known as the Cambridge half life.

In 1960, Mr. Willard F. Libby was awarded the Nobel Prize in Chemistry in recognition of his efforts to develop radiocarbon dating.

Radio carbon revolution helped more precise historical chronologies across geography and cultures. [R. F. Flint, E. S. Deevey, Jr., and Elizabeth G. Weinman, (Eds.), American Journal of Science, Radiocarbon Supplement, Vol. II (1960),]

How Carbon -14 Dating works

Radiocarbon dating is essentially a method of measuring residual radioactivity, It starts with cosmic rays, subatomic particles of matter, constantly falling on the Earth from all directions. When cosmic rays reach Earth's upper atmosphere, physical and chemical interactions produce the radioactive isotope carbon-14.

Radiocarbon dating can be performed on any object that has ever existed. These include parts of animals, people and plants, but also paper made from reeds, leather made from animal skins, tree trunks used to build houses, and more, The amount of carbon-14 in the air and in all living things is nearly constant at all times. Carbon-14 atoms continually decay but are replaced by new carbon-14 atoms at a constant rate ,At this point, your body contains a certain proportion of carbon-14 atoms, and all living plants and animals contain the same proportion. [Beta Analytic (2019). What is Carbon-14 (14C) Dating? Carbon Dating Definition.]

Carbon-14 is continuously formed in the upper atmosphere through the action of cosmic ray neutrons on nitrogen-14 atoms. It is rapidly oxidized into carbon dioxide in the air and enters the global carbon cycle.

Plants and animals absorb carbon 14 from carbon dioxide during their lives. When they die, they stop exchanging carbon with the biosphere, and their carbon-14 content begins to decline at a rate determined by the laws of radioactive decay, Animals get their dose of

C-14 from the food they eat and When the organism (or tissue) dies, the absorption of C-14 ceases The half-life of C-14 decaying to nitrogen is 5730 years, so the concentration halves every 5730 years.

Radioactive carbon (C-14) B decays into nitrogen (N14) by emitting electrons (e-) and antineutrinos (v-) which have no mass or charge. [Beta Analytic (2015). What is Carbon-14 (14C) Dating? Carbon Dating Definition.]

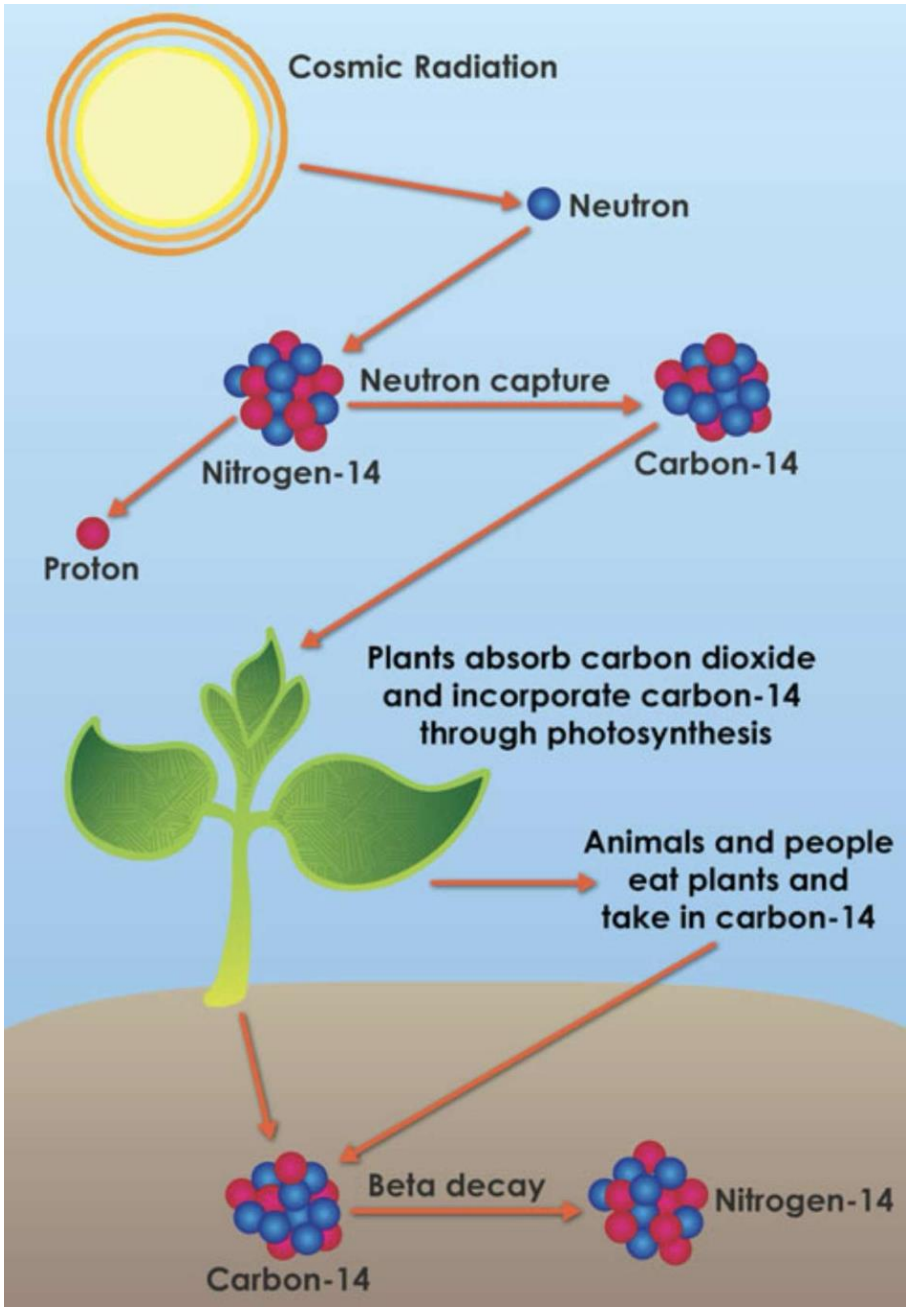

Fig 1: Schematic of 14C production and decay in the atmosphere. 14C is produced in the atmosphere by cosmic neutrons colliding with Nitrogen atoms. The newly formed 14C is oxidized to 14CO2 where it then enters the biosphere. Following an organisms death, radioactive decay occurs converting the 14C back to 14N. [earthsciences.anu.edu.au, n.d.]

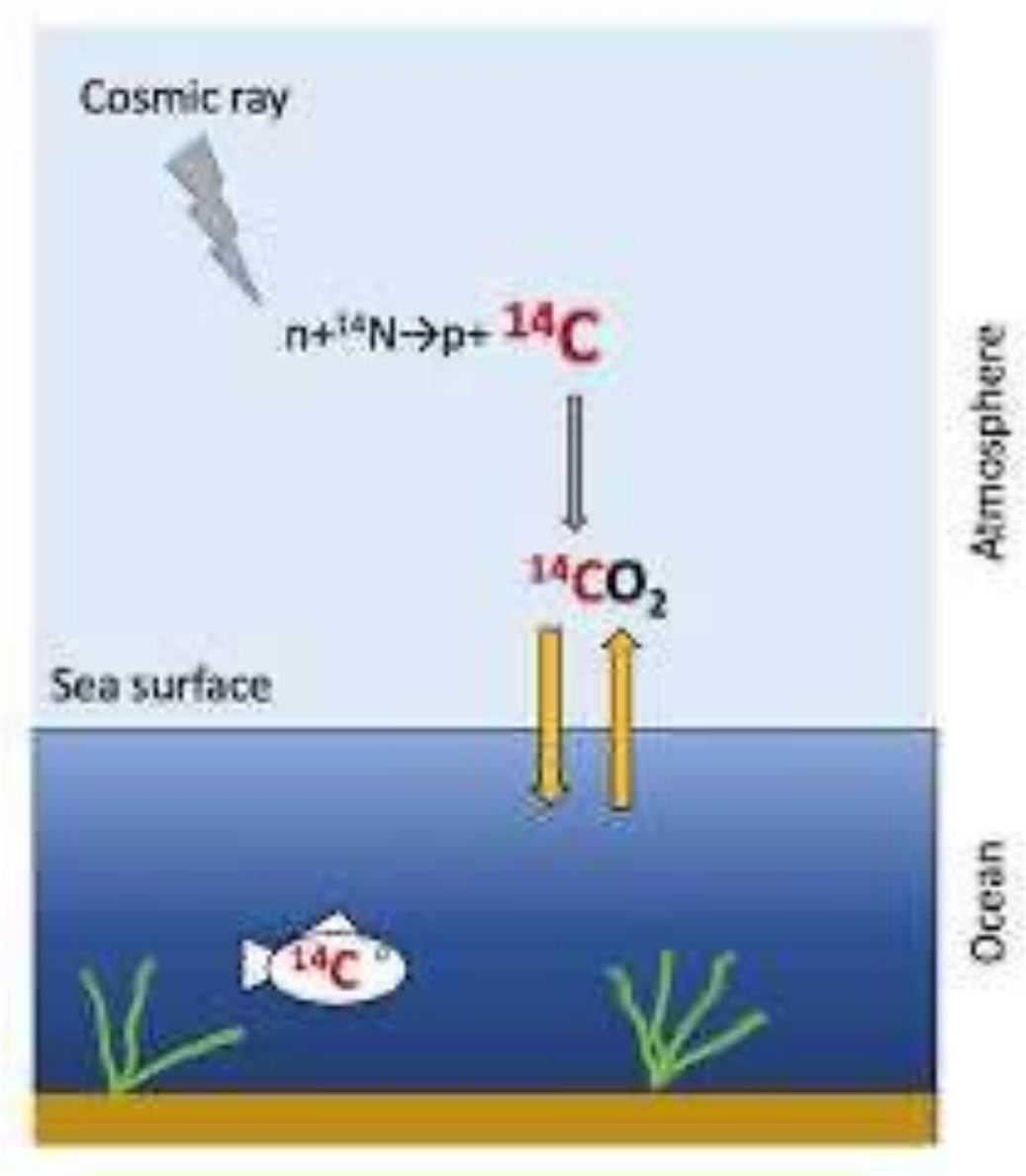

Fig 2: Schematic representation of the mechanism underlying the uptake of carbon from marine organisms. [Quarta et al., 2021]

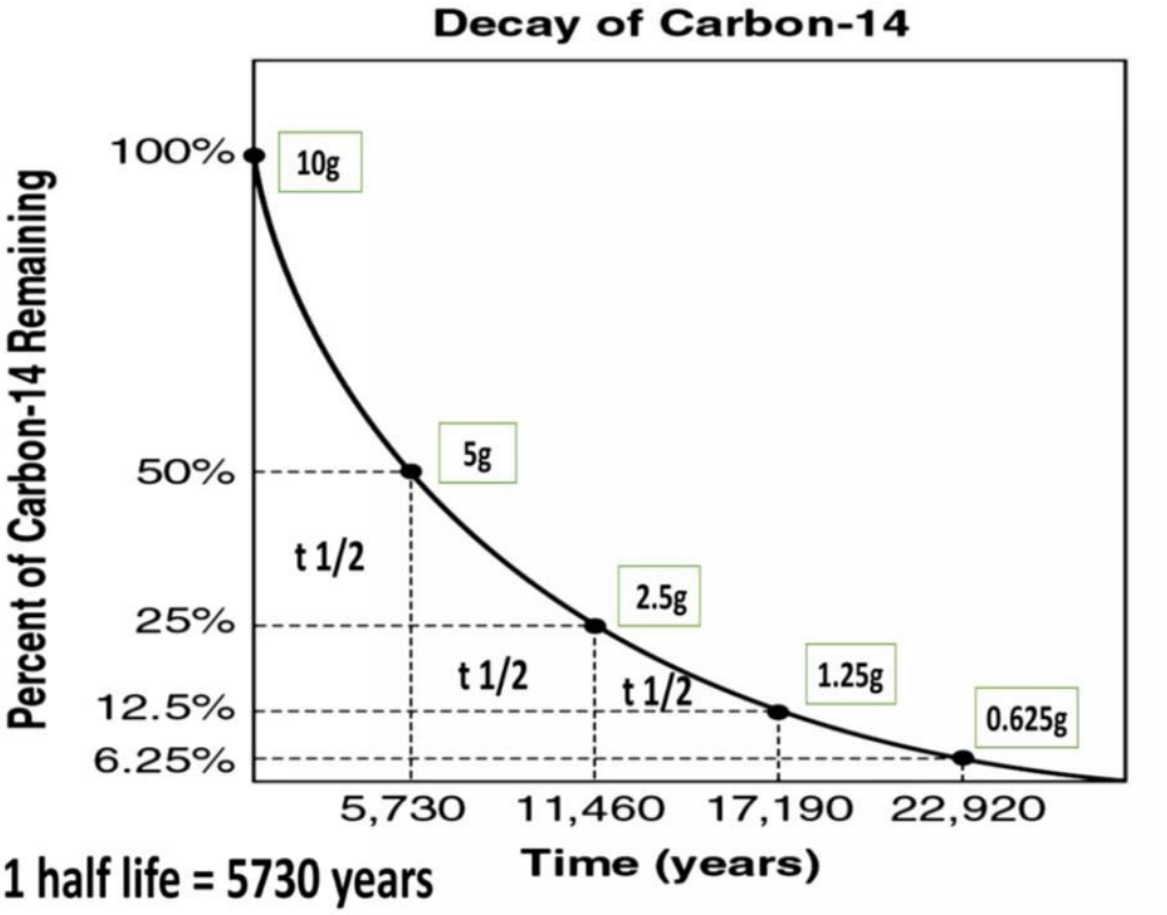

Fig 3: Carbon 14 decay curve , source. [Stroski, 2021]

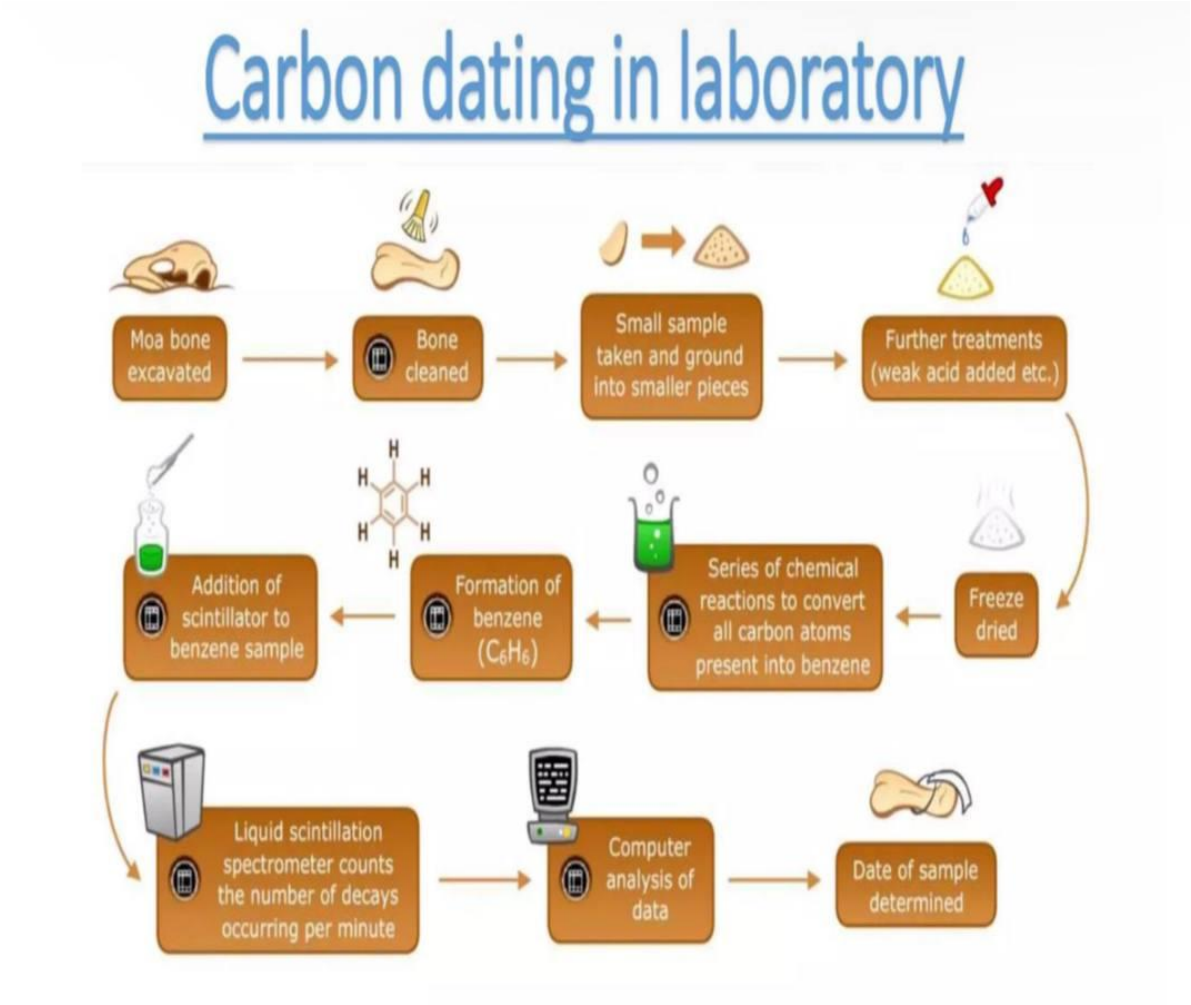

Fig 4: Carbon 14 dating process. [radioisotope.2009]

Carbon – 14 dating process

Moa bone excavated: The Wairau Bar in Blenheim is one of the oldest archaeological sites in New Zealand. Amongst the artefacts that have been found are ancient moa bones. Some of these have been sent to the Waikato Radiocarbon Dating Laboratory for analysis.

Bone cleaned: First, the lab will test the bone to see how much protein remains in it, because it's the protein fraction of the bone that they actually date. Once they know that there is sufficient protein remaining, they clean the surface of the bone to remove contaminants like dirt, charcoal or, in some cases, glue that the archaeologists have used to mend the bone fragments

Small sample taken and ground into smaller pieces: The cleaned bone sample is then ground up into smaller pieces to speed up chemical reaction with the acid in the next stage.

Further treatments (weak acid added etc.): The ground-up bone is treated with hydrochloric acid, which dissolves out the hard part of the bone. The remaining material goes through a gelatinisation process to free up the bone protein. Filtration during this phase allows contaminants to be successfully removed.

Freeze dried: The sample is freeze dried to remove excess water. After this process, the resulting material has a spongy texture with an off-white colour. It is now ready for testing.

Series of chemical reactions to convert all carbon atoms present into benzene: The pre-treated sample is loaded onto a quartz silica boat, which is loaded into a combustion tube. It is a long tube which is hooked up to a vacuum line. All air is evacuated from the vacuum line because it has C-14 in it and is a potential contaminant. Then a stream of oxygen is added into the system and the sample is combusted. It is during this stage that the carbon present in the sample is converted into carbon dioxide. The carbon dioxide is collected and bubbled through various chemicals in the line, which purify it, and the amount of carbon dioxide that has been collected is measured.

Formation of benzene (C_6H_6): The carbon dioxide formed in the combustion stage is heated in the presence of pure lithium metal, which produces lithium carbide. When all of the carbon dioxide has reacted, distilled water is added to

the lithium carbide and a chemical reaction occurs, resulting in the production of acetylene gas. This gas is then passed through a vanadium-based catalyst column, which produces liquid benzene (C_6H_6).

Addition of scintillator to benzene sample: A scintillator chemical (butyl-PBD) is added to the liquid benzene. Fiona is wearing an aspirator because of the carcinogenic properties of benzene. Special silica glass vials are used to contain the mixture of benzene and PBD.

Liquid scintillator spectrometer counts the number of decays occurring per minute: The silica glass vials are loaded into the liquid scintillation spectrometer. The C-14 atoms present in the benzene decay at a certain rate. The scintillator chemical butyl-PBD picks up each decay event and emits a tiny flash of light that the spectrometer is programmed to detect and count. In addition to the moa sample, control samples are also measured at the same time. The decay events for each sample are measured over a week.

Computer analysis of data: The results from the liquid scintillation spectrometer are carefully analysed and provide a radiocarbon age for the sample. To obtain a calendar age for the sample, this radiocarbon age needs to be compared against samples of known age by means of a calibration curve using a specially designed computer software application. This application uses a terrestrial calibration curve to calculate the calendar age. [Lee-Thorp, J. (2008).]

Determination of Age

N=(C14/C12 ratio in the dead organism)

$N_\circ$ =(C14/C12 ratio in the living organism)

t= age of the organism

K= disintegration constant

We know that, [Humphreys, D.R.2011]

$$N = N_\circ\, e^{-Kt}$$

$$\frac{N}{N_\circ} = e^{-Kt}$$

$$or \quad \ln\left(\frac{N}{N_\circ}\right) = -Kt$$

$$2.303\, log_{10}\left(\frac{N}{N_\circ}\right) = -t \times \frac{0.693}{t_{\frac{1}{2}}} \quad c_{14}$$

$$t = -\left\{2.303 \times \frac{\left(t_{\frac{1}{2}}\right) c_{14}}{0.693}\right\} \times log_{10}\left(\frac{N}{N_\circ}\right)$$

$$\boldsymbol{t = \left\{2.303 \times \frac{\left(t_{\frac{1}{2}}\right) c_{14}}{0.693}\right\} \times log_{10} \frac{(c14/c12\ ratio\ in\ the\ living\ organism)}{(c14/c12\ ratio\ in\ the\ dead\ organism)}}$$

Plot

If $A_\circ$ and A_n, are activities at time zero and after n half life period respectively then,

$$\boldsymbol{A_n = A_n(0.5)^n}$$

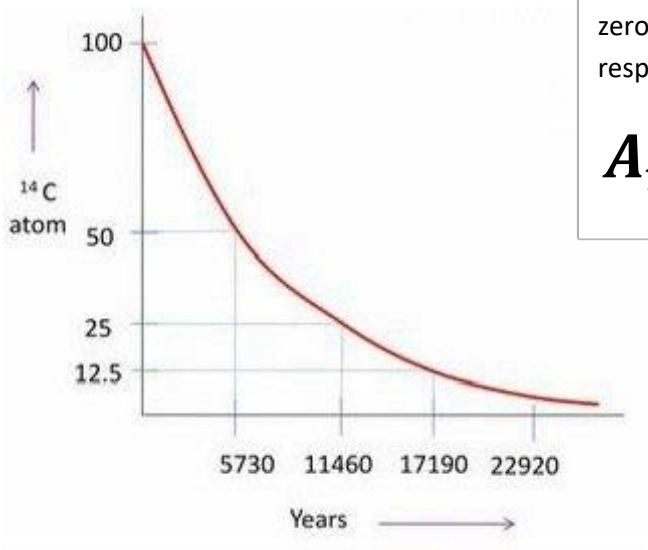

Fig 5: Half-life C-14 Dating . [Isotopes in Palaeoenvironmental Research.Melanie J. Leng (Editor), 2006, Springer, Berlin Germany Series: Developments in Paleoenvironmental Research]

Methods of measuring Carbon-14

There are three basic methods :

1- Gas Proportional Counting (Radiometric dating)

Gas proportional counting is a traditional radiometric dating technique that counts the beta particles emitted by a given sample. Radiometric dating is used to detect beta particles produced by the decay of carbon-14 atoms. Beta particles are the product of radioactive carbon decay. In this method, a carbon sample is first converted into carbon dioxide gas and then measured in a gas radiometer. Use a gas proportional counter (a type of Geiger counter) or a liquid scintillation counter. It's cheap and takes about a month to get satisfactory statistics. [Bulman, P. (2012a)]

2- Liquid Scintillation Counting

Liquid scintillation counting is another radiocarbon dating method popular in the 1960s. In this method, the sample is in liquid form and scintillator is added. When this scintillator interacts with beta particles, a flash of light is produced. The vial containing the sample is passed between two photomultiplier tubes, and flashes are counted only when both devices register them. [Bulman, P. (2012a)]

3- Accelerator Mass Spectrometry

is a modern radiocarbon dating method that is considered to be the more efficient way to measure radiocarbon content of a sample, count the number of carbon 14 atoms present in the sample In this method, the carbon 14 content is directly measured relative to the carbon 12 and carbon 13 present. The method does not count beta particles but the number of carbon atoms present in the sample and the proportion of the isotopes ,It is expensive and it takes about a week and It requires only about a gram.It is a good method for dating specific samples. [Miami, B.A. 4985 S.W. 74th C. (2015a).]

Fig 7: Accelerator Mass Spectrometer dating . [Bulman, P. (2012a)]

fig 8: Liquid Scintillation counter. [Bulman, P. (2012a)]

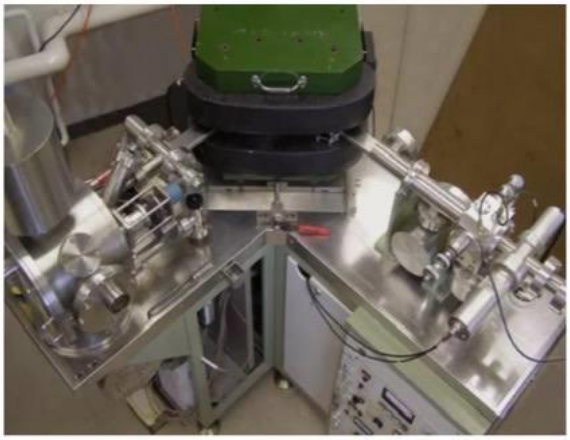

Fig 9: Radiometric.[Bulman, P. (2012b)]

Application

The applications of carbon-14 dating are diverse. Over the years, carbon-14 dating has also been used in geology, hydrology, geophysics, atmospheric science, oceanography, paleoclimatology, and even biomedicine. Carbon dating is useful when archaeologists need to know the approximate date of a fossil or other object. Carbon dating can be used to determine the age of trees, mummies, fossils or other organic material. Radiocarbon dating can be used to date carbonaceous pigments such as charcoal and even cave paintings. [Marra, J.F. (2019)]

• Samples that have been radiocarbon dated since the introduction of this method include

• Charcoal, wood, twigs, seeds, bones, shells, leather, peat

• lake mud, soil, hair, ceramics, pollen

• Frescoes, corals, bloodstains, fabrics

• Paper or parchment, resin and water. [Marra, J.F. (2019)]

In important applications (**Archaeological dating, Geochronology, Forensic science**)

Archaeological dating: Carbon 14 dating is used to determine the ages of artifacts found at archaeological sites, providing insights into human history and cultural evolution.

Geological Samples: Scientists use carbon dating to establish the ages of geological samples, such as rocks and fossils, to better understand Earth's history.

Ancient Human Remains: Carbon dating allows scientists to estimate the age of ancient human remains, providing valuable information about human migration patterns and the history of our species.

Fig 10 : Archaeological dating

Fig 11: Ancient Human Remains

Fig 12 : Geological Samples

Half-life

The time taken for half a radioactive sample to decay into something else, Half-life, in radioactivity, is the time required for half of the nuclei of a radioactive sample to decay (spontaneously transform into other nuclides by emitting particles and energy), or equivalently, the time required for the amount per second of decay of a radioactive substance to decrease Half done. Carbon-14 has a half-life of approximately 5,730 years.

- ➢ Decay: Carbon-14 is a radioactive isotope, which means it decays over time.
- ➢ Radioisotopes: During radioactive decay, carbon-14 emits radiation and is converted into stable carbon.
- ➢ Stable carbon: The decay process of carbon 14 produces a stable form of carbon called carbon 12. [Koppes , S. and Lerner, L. (2023).]

Why Carbon 14 ?

Carbon dating is performed on objects containing fragments of organic matter, carbonbased substance once found in living plants and animals, Not all carbon atoms are the same. About 99% of carbon atoms have a nucleus of 6 protons and 6 electrons and an atomic mass of 12. About one percent of carbon atoms have an extra neutron in their nucleus, giving them an atomic mass of 13. A very small number of carbon atoms (about one in a trillion) have two extra neutrons, giving their atomic mass 14. These different types of carbon atoms are called isotopes.

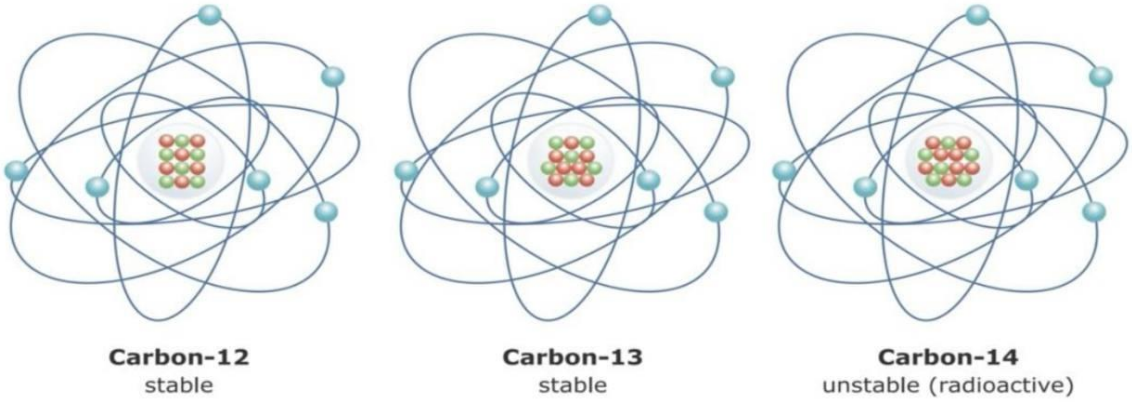

Fig 13 : Three different types (isotopes) of carbon atoms. [Marra, J.F. (2019)]

Carbon-14 atoms are unstable and, over time, their own atoms disappear or decay. This fact is crucial to understanding how carbon dating is used to determine the age of objects. "Since all living things are made up of organic molecules, they must have a source of carbon to exist. For most organisms, this carbon source is carbon dioxide (CO2) in the atmosphere. Carbon atoms in the atmosphere contain the proportions described above of three isotopes

The same ratio exists for organisms that obtain carbon from the atmosphere. These parts remain in their bodies as long as they live, as carbon is constantly renewed in organisms. However, when an organism dies, the carbon is no longer replaced. Imagine pollen grains being picked up by the wind and carried into the air. After traveling hundreds of kilometers, the pollen grains fall on the glacier and are buried under the many snowfalls each year. Thousands of years later, a geologist took an ice core from a glacier and found the same pollen grains in his ice sample. Can he determine the age of the pollen grains? If so, he also knows how old this part of the glacier is. [Marra, J.F. (2019)]

Carbon dating allows geologists to accurately estimate the age of a sample. By measuring the ratio of carbon-14 to all carbon atoms in the pollen grains, he knew how much carbon-14 decayed, the extent of decay will reveal the age of the pollen grain.

Limitation

• Dating is not possible for samples older than 60,000 years.

• Dating is possible only for objects containing organic material.

• Objects that are parts of living things only could be dated.

• Emission from fossil fuels limit carbon dating.

• The material being dated must have measurable amounts of the parent or the daughter isotopes.

• Carbon dating can only be done on some materials, hence is not useful for determining the age of sedimentary rocks, and the method of carbon dating can be prohibitively expensive.

• Samples can be contaminated by other carbon-containing materials.

• The dates obtained from radiocarbon dating are not infallible, that is, in general, single dates should not be trusted. Thus, multiple samples need to be collected and dated. [American Chemical Society National Historic Chemical Landmarks.2017]

Conclusion

In conclusion, carbon-14 dating is a powerful tool that has revolutionized our understanding of the past. By measuring the radioactive decay of carbon-14 atoms in organic materials, scientists can determine the age of once-living organisms with remarkable accuracy. This technique has been invaluable in fields like archaeology, geology, and paleontology, allowing us to piece together the timeline of human and natural history. Carbon dating technology is effective technology to find out age of objects up to 60,000 years old. Most of every field of science utilises carbon dating ,Carbon dating is in danger due to excess burning of fossil fuel. The key to carbon-14 dating is the constant rate of decay of radioactive carbon-14 atoms, which are continuously formed in the upper atmosphere and incorporated into living organisms through photosynthesis and the food chain. As an organism dies, the carbon-14 within it begins to decay at a predictable rate, allowing us to calculate how long ago it lived. With the ability to date organic materials ranging from ancient wood to fossilized bones, carbon-14 dating has provided a wealth of insights into the past, from the emergence of human civilizations to the extinction of the dinosaurs. While carbon-14 dating is not without its limitations, such as the need for well-preserved samples and the restricted time frame of approximately 50,000 years, it remains an invaluable tool in the quest to unravel the mysteries of our world. As we continue to refine and expand our understanding of this dating method, we can expect even more groundbreaking discoveries in the years to come, shedding light on the evolution of life on Earth and the rich tapestry of human history.

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