Tracing Time: The Science and Applications of Radiocarbon

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Introduction

In 1934, F.N.D. Kurie at Yale University provided the first evidence for the existence of radiocarbon (carbon-14, ^{14}C). Radiocarbon is a radioactive isotope of carbon, consisting of 6 protons and 8 neutrons. As a cosmogenic radionuclide, ^{14}C is continually produced through the interaction of cosmic rays with the atmosphere and the Earth's surface. The ^{14}C nucleus is unstable and undergoes spontaneous decay by emitting a β particle (electron):

$$^{14}_{6}C \rightarrow {}^{14}_{7}N + \beta^{-} + \gamma(energy)$$

Radiocarbon dating (also known as ^{14}C dating or carbon dating) is a widely used method for reliable chronometric analysis of archaeological materials ranging from approximately 55,000 years ago to the present. This technique was developed in the late 1940s by Willard F. Libby and two graduate students, Arnold and Anderson, at the University of Chicago. The ^{14}C dating method relies on the assumption that the rate of atmospheric formation of ^{14}C remains constant (Hajdas *et al*., 2021).

Measurement Methods

The radiocarbon dating method has been in use for around 50 years. The first measurement of ^{14}C was conducted by W.F. Libby's laboratory in Chicago in 1949, and the first age results were published in 1951. A crucial element in determining the age was the precise measurement of the radiocarbon half-life.

1. **Radiometric counting** measures the amount of ^{14}C in a sample by detecting its radioactivity. This involves converting the carbon in the sample into a gas like CO_2, methane, or benzene, which is then analysed in a radiation detector.

There are two main types of counting systems:

- *Gas proportional counting*: The sample is converted into CO_2 or methane and introduced into a proportional counter. The decay of ^{14}C causes an electrical discharge in the gas, which is detected electronically. This method is sensitive and requires careful cleaning of CO_2 to ensure accurate readings (Fig 1).
- *Liquid scintillation counting*: The sample is converted into benzene, mixed with a scintillation cocktail. When a 14C atom decays, it emits light, which is detected by photomultiplier tubes. The system's efficiency is improved by using two photomultipliers and a coincidence unit to reduce background noise (Tudyka *et al*., 2017).

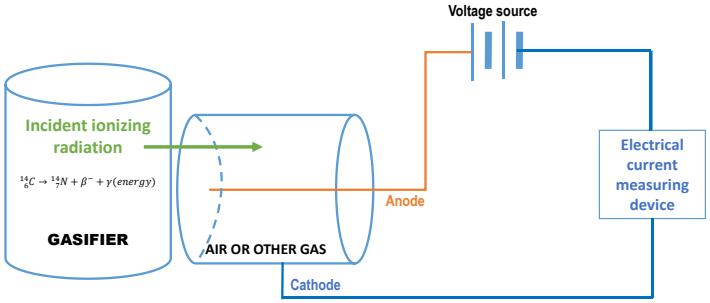

Fig 1. Schematic diagram of Gas Proportional Counter

2. **Accelerator Mass Spectrometry (AMS)** uses a particle accelerator to directly count ^{14}C atoms, even in tiny or degraded samples. This technique is highly precise and can detect ^{14}C in the presence of more abundant isotopes like ^{12}C and ^{13}C (Kutschera, 2013).

Working of AMS

A nuclear particle accelerator consists essentially of two linear accelerators joined end-to-end, with the join section (called the terminal) charged to a very high positive potential (3 million volts or higher) (Fig 2).

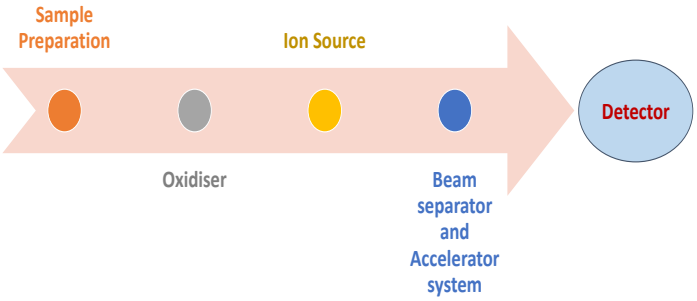

Fig 2. Working Principle of an AMS

Occurrence of Radiocarbon in Different Ecosystems

Radiocarbon in the Oceans

Most of the ^{14}C in seawater comes from the atmosphere through the exchange of CO_2. This carbon is quickly absorbed by plants, leading to a decrease in ^{14}C levels with depth due to radioactive decay and isolation from the atmosphere. The migration of ^{14}C-depleted water back to the surface causes surface DIC to appear older than expected, a phenomenon known as the "reservoir effect" (Heaton *et al*., 2020). The age of surface waters varies depending on the amount of upwelling and down-welling in different ocean regions.

Radiocarbon in Corals

The ocean plays a key role in the Earth's climate system, exchanging heat, freshwater, and CO_2 with the atmosphere. Changes in sea surface temperature, such as those linked to ENSO events and the Pacific Decadal Oscillation, influence the ocean mixing rates. These variations, occurring on inter-annual and multi-decadal scales, affect the distribution of radiocarbon in the oceans.

Radiocarbon in Terrestrial Systems

Terrestrial ecosystems experience slow carbon transfer compared to the atmosphere and oceans. Carbon enters these systems mainly via atmospheric CO_2 captured by plants during photosynthesis. Once plants die, their carbon remains in the ecosystem, decomposed by microorganisms and recycled. The movement of ^{14}C through these processes helps track the turnover rates of organic matter in soils, providing insights into how carbon cycles within terrestrial ecosystems over time.

Radiocarbon and Climate Change

Preindustrial Radiocarbon Distribution: Before 1850, the atmosphere's $^{14}CO_2$ levels were influenced solely by cosmogenic production, radioactive decay, and land-ocean exchanges. Cosmogenic production increased ^{14}C levels in the atmosphere by about 9 % per year, while the terrestrial biosphere and oceans had negative influences due to the radioactive decay of carbon. The ocean's influence was particularly significant, with its long carbon residence time. Throughout the last ice age, the $\Delta^{14}CO_2$ was as high as +600 %. Over the past 10,000 years, $\Delta^{14}CO_2$ has remained relatively stable, showing fluctuations tied to solar activity, which impacts cosmogenic ^{14}C production (Wood, 2015).

The "Suess Effect" (1890–1945): The first evidence of human impact on atmospheric $^{14}CO_2$ was seen by Suess in 1955, showing a decline in $^{14}CO_2$ in tree-ring records from North America in the early 1900s. This drop was due to the addition of ^{14}C-free fossil fuel CO_2 to the atmosphere, a phenomenon now called the "Suess effect." This decrease was greater in regions with heavy local combustion sources. The magnitude of the effect varied regionally, providing early indications that fossil fuel CO_2 emissions could be estimated from regional records.

The "Bomb Effect" (1945–1985): The first direct measurements of atmospheric $^{14}CO_2$ began in 1954. The testing of nuclear weapons in the 1950s and 1960s significantly increased the amount of ^{14}C in the atmosphere, particularly in the Northern Hemisphere, where levels peaked in 1963. After 1963, $^{14}CO_2$ levels began to fall as the negative iso-flux from the oceans and terrestrial biosphere dominated over the positive contributions from the stratosphere.

The Post-Bomb Period (1985 – Present): Following the nuclear bomb tests, the atmospheric ^{14}C content began to decrease as the tropospheric CO_2 content adjusted to the addition of fossil fuel CO_2. At the same time, carbon reservoirs in the land and oceans were altered. This shift in carbon exchange has impacted the tropospheric $^{14}CO_2$ concentration.

The Future of Atmospheric Radiocarbon

As of 2014, atmospheric $\Delta^{14}CO_2$ is about 30 % higher than preindustrial levels. If fossil fuel emissions continue to rise, it is expected that atmospheric $^{14}CO_2$ will fall below preindustrial levels within the next decade. By 2100, $\Delta^{14}CO_2$ might decrease to −150 %, reversing the current pattern, with even deep ocean waters contributing ^{14}C back to the atmosphere.

Conclusion

Radiocarbon dating has proven to be an invaluable tool for understanding both historical and environmental changes over the past few millennia. Through various measurement techniques such as gas proportional counting, liquid scintillation counting, and accelerator mass spectrometry (AMS), scientists have been able to accurately assess the presence and abundance of ^{14}C in various samples. These techniques have not only revolutionized the field of archaeology and paleoclimatology but have also provided critical insights into the effects of human

activities, such as fossil fuel burning and nuclear testing, on the carbon cycle. As radiocarbon levels in the atmosphere continue to be influenced by anthropogenic factors, especially the ongoing increase in fossil fuel emissions, the study of radiocarbon dynamics is becoming even more essential. Understanding the fluctuations in $\Delta^{14}CO_2$ levels in response to these activities, as well as the interactions between land, ocean, and atmospheric carbon reservoirs, will be crucial for predicting future climate scenarios and for developing strategies to mitigate the impacts of climate change.

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