Carbon-14

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This article is about the radioactive isotope. For the scientific journal, see Radiocarbon (magazine).

Carbon-14, ^{14}C, or **radiocarbon**, is a radioactive isotope of carbon with a nucleus containing 6 protons and 8 neutrons. Its presence in organic materials is the basis of the radiocarbon dating method pioneered by Willard Libby and colleagues (1949) to date archaeological, geological and hydrogeological samples. Carbon-14 was discovered on 27 February 1940, by Martin Kamen and Sam Ruben at the University of California Radiation Laboratory in Berkeley. Its existence had been suggested by Franz Kurie in 1934.[2]

Carbon-14 Full table	
General	
Name, symbol	radiocarbon, ^{14}C
Neutrons	8
Protons	6
Nuclide data	
Natural abundance	1 part per trillion
Half-life	5,730 ± 40 years
Isotope mass	14.003241 u
Spin	0+
Decay mode	**Decay energy**
Beta	0.156476[1] MeV

There are three naturally occurring isotopes of carbon on Earth: 99% of the carbon is carbon-12, 1% is carbon-13, and carbon-14 occurs in trace amounts, *i.e.*, making up about 1 part per trillion (0.0000000001%) of the carbon in the atmosphere. The half-life of carbon-14 is 5,730±40 years.[3] Carbon-14 decays into nitrogen-14 through beta decay.[4] The primary natural source of carbon-14 on Earth is cosmic ray action upon nitrogen in the atmosphere, and it is therefore a cosmogenic nuclide. However, open-air nuclear testing between 1955–1980 contributed to this pool.

The different isotopes of carbon do not differ appreciably in their chemical properties. This is used in chemical and biological research, in a technique called carbon labeling: carbon-14 atoms can be used to replace nonradioactive carbon, in order to trace chemical and biochemical reactions involving carbon atoms from any given organic compound.

Radioactive decay and detection

Carbon-14 goes through radioactive beta decay:

$$^{14}_{6}C \rightarrow {}^{14}_{7}N + e^{-} + \bar{\nu}_e$$

By emitting an electron and an electron antineutrino, one of the neutrons in the carbon-14 atom decays to a proton and the carbon-14 (half-life of 5730 years) decays into the stable (non-radioactive) isotope nitrogen-14.

The emitted beta particles have maximum energy of 156 keV, while their average energy is 49 keV. These are relatively low energies; the maximum distance traveled is estimated to be 22 cm in air and 0.27 mm in body tissue. The fraction of the radiation transmitted through the dead skin layer is estimated to be 0.11. Small amounts of carbon-14 are not easily detected by typical Geiger–Müller (G-M) detectors; it is estimated that G-M detectors will not normally detect contamination of less than about 100 000 disintegration per minute (0.05 μCi). Liquid scintillation counting is the preferred method.[5] The G-M counting efficiency is estimated to be 3%. The half-distance layer in water is 0.05 mm.[6]

Radiocarbon dating

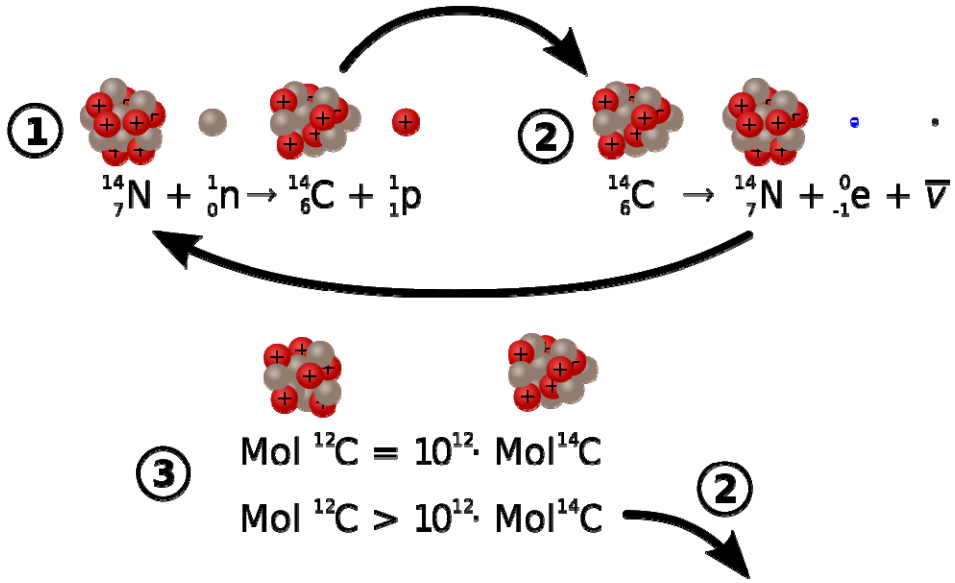
Main article: Radiocarbon dating

Radiocarbon dating is a radiometric dating method that uses (^{14}C) to determine the age of carbonaceous materials up to about 60,000 years old. The technique was developed by Willard Libby and his colleagues in 1949[7] during his tenure as a professor at the University of Chicago. Libby estimated that the radioactivity of exchangeable carbon-14 would be about 14 disintegrations per minute (dpm) per gram of pure carbon, and this is still used as the activity of the *modern radiocarbon standard*.[8][9] In 1960, Libby was awarded the Nobel Prize in chemistry for this work.

One of the frequent uses of the technique is to date organic remains from archaeological sites. Plants fix atmospheric carbon during photosynthesis, so the level of ^{14}C in plants and animals when they die approximately equals the level of ^{14}C in the atmosphere at that time. However, it decreases thereafter from radioactive decay, allowing the date of death or fixation to be estimated. The initial ^{14}C level for the calculation can either be estimated, or else directly compared with known year-by-year data from tree-ring data (dendrochronology) up to 10,000 years ago (using overlapping data from live and dead trees in a given area), or else from cave deposits (speleothems), back to about 45,000 years before the present. A calculation or (more accurately) a direct comparison of carbon-14 levels in a sample, with tree ring or cave-deposit carbon-14 levels of a known age, then gives the wood or animal sample age-since-formation.

Origin

Natural production in the atmosphere



1: Formation of carbon-14
2: Decay of carbon-14
3: The "equal" equation is for living organisms, and the unequal one is for dead organisms, in which the C-14 then decays (See 2).

Carbon-14 is produced in the upper layers of the troposphere and the stratosphere by thermal neutrons absorbed by nitrogen atoms. When cosmic rays enter the atmosphere, they undergo various transformations, including the production of neutrons. The resulting neutrons (^{1}n) participate in the following reaction:

$$^{1}n + {}^{14}N \rightarrow {}^{14}C + {}^{1}p$$

The highest rate of carbon-14 production takes place at altitudes of 9 to 15 km (30,000 to 50,000 ft) and at high geomagnetic latitudes.

As of 2008, the rate of carbon-14 production was poorly known – while the reaction can be modelled or the current concentrations and the global carbon budget can be used to backtrack, attempts to directly measure the production rate had not agreed with these models very well. Production rates vary because of changes to the cosmic ray flux incident, such as supernovae, and due to variations in the Earth's magnetic field. The latter can create significant variations in carbon-14 production rates, although the changes of the carbon cycle can make these effects difficult to tease out.[10]

The natural atmospheric yield of carbon-14 has been estimated to be about 22 000 atoms ^{14}C per meter square of the surface of the earth per second, resulting in the global production rate of about 1 PBq/a.[11] Another estimate of the average production rate[12] gives a value of 20 500 atoms $m^{-2}s^{-1}$. Occasional spikes are possible; for example, there is evidence for an unusual 10-fold increase of the production rate in AD 774–775.[13]

Other carbon-14 sources

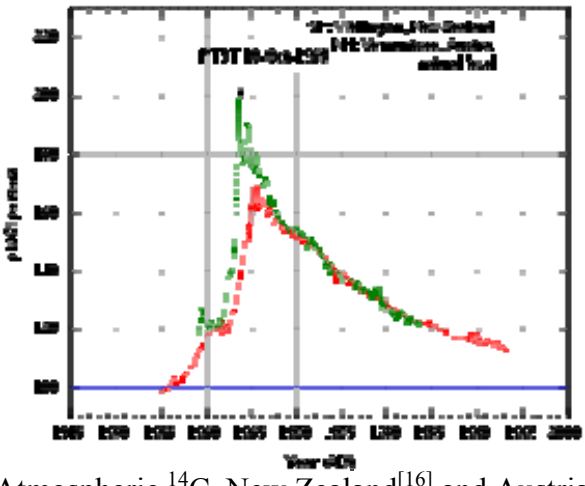
Carbon-14 can also be produced by other neutron reactions, including in particular $^{13}C(n,gamma)^{14}C$ and $^{17}O(n,alpha)^{14}C$ with thermal neutrons, and $^{15}N(n,d)^{14}C$ and $^{16}O(n,^{3}He)^{14}C$ with fast neutrons.[14] The most notable routes for ^{14}C production by thermal neutron irradiation of targets (e.g., in a nuclear reactor) are summarized in the table.

Carbon-14 may also be radiogenic (cluster decay of ^{223}Ra, ^{224}Ra, ^{226}Ra). However, this origin is extremely rare.

^{14}C production routes[15]

Parent isotope	Natural abundance, %	Cross section for thermal neutron capture, b	Reaction
^{14}N	99.634	1.81	$^{14}N(n,p)^{14}C$
^{13}C	1.103	0.0009	$^{13}C(n,\gamma)^{14}C$
^{17}O	0.0383	0.235	$^{17}O(n,\alpha)^{14}C$

Formation during nuclear tests



Atmospheric ^{14}C, New Zealand[16] and Austria.[17] The New Zealand curve is representative for the Southern Hemisphere, the Austrian curve is representative for the Northern Hemisphere. Atmospheric nuclear weapon tests almost doubled the concentration of ^{14}C in the Northern Hemisphere.[18]

The above-ground nuclear tests that occurred in several countries between 1955 and 1980 (see nuclear test list) dramatically increased the amount of carbon-14 in the atmosphere and subsequently in the biosphere; after the tests ended, the atmospheric concentration of the isotope began to decrease.

One side-effect of the change in atmospheric carbon-14 is that this has enabled some options (e.g. bomb-pulse dating[19]) for determining the birth year of an individual, in particular, the amount of carbon-14 in tooth enamel,[20][21] or the carbon-14 concentration in the lens of the eye.[22]

Occurrence

Dispersion in the environment

After production in the upper atmosphere, the carbon-14 atoms react rapidly to form mostly (about 93%) ^{14}CO (carbon monoxide), which subsequently oxidizes at a slower rate to form $^{14}CO_2$, radioactive carbon dioxide. The gas mixes rapidly and becomes evenly distributed throughout the atmosphere (the mixing timescale in the order of weeks). Carbon dioxide also dissolves in water and thus permeates the oceans, but at a slower rate.[10] The atmospheric half-life for removal of $^{14}CO_2$ has been estimated to be roughly 12 to 16 years in the northern hemisphere. The transfer between the ocean shallow layer and the large reservoir of bicarbonates in the ocean depths occurs at a limited rate.[15]

Total inventory

The inventory of carbon-14 in Earth's biosphere is about 300 megacuries (11 EBq), of which most is in the oceans.[23] The following inventory of carbon-14 has been given:[11]

- Global inventory: ~8500 PBq (about 50 t)
  - Atmosphere: 140 PBq (840 kg)
  - Terrestrial materials: the balance
- From nuclear testing (till 1990): 220 PBq (1.3 t)

In fossil fuels

Most man-made chemicals are made of fossil fuels, such as petroleum or coal, in which the carbon-14 should have long since decayed. However, such deposits often contain trace amounts of carbon-14 (varying significantly, but ranging up to 1% the ratio found in living organisms, a concentration comparable to an apparent age of 40,000).[24] This may indicate possible contamination by small amounts of bacteria, underground sources of radiation causing the $^{14}N(n,p)\ ^{14}C$ reaction, direct uranium decay (although reported measured ratios of $^{14}C/U$ in uranium-bearing ores[25] would imply roughly 1 uranium atom for every two carbon atoms in order to cause the $^{14}C/^{12}C$ ratio, measured to be on the order of 10^{-15}), or other unknown secondary sources of carbon-14 production.

Presence of carbon-14 in the isotopic signature of a sample of carbonaceous material possibly indicates its contamination by biogenic sources or the decay of radioactive material in surrounding geologic strata. In connection with building the Borexino solar neutrino observatory, petroleum feedstock (for synthesizing the primary scintillant) was obtained with low ^{14}C content. In the Borexino Counting Test Facility, a $^{14}C/^{12}C$ ratio of 1.94×10^{-18} was determined;[26] probable reactions responsible for varied levels of ^{14}C in different petroleum reservoirs, and the lower ^{14}C levels in methane, have been discussed by Bonvicini et al.[27]

In the human body

Since essentially all sources of human food are derived from plants, the carbon that comprises our bodies contains carbon-14 at the same concentration as the atmosphere. The rates of disintegration of potassium-40 and carbon-14 in the normal adult body are comparable (a few thousand disintegrated nuclei per second).[28] The beta-decays from external (environmental) radiocarbon contribute approximately 0.01 mSv/year (1 mrem/year) to each person's dose of ionizing radiation.[29] This is small compared to the doses from potassium-40 (0.39 mSv/year) and radon (variable).

Carbon-14 can be used as a radioactive tracer in medicine. In the initial variant of the urea breath test, a diagnostic test for *Helicobacter pylori*, urea labeled with approximately 37 kBq (1.0 µCi) carbon-14 is fed to a patient (i.e. 37,000 decays per second). In the event of a *H. pylori* infection, the bacterial urease enzyme breaks down the urea into ammonia and radioactively-labeled carbon dioxide, which can be detected by low-level counting of the patient's breath.[30] The 14-C urea breath test has been largely replaced by the 13-C urea breath test which has no radiation issues.