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RESEARCH PAPER

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Carbon Isotopes: A Review

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ABSTRACT

The name isotope comes from Greek isos meaning equal and topos meaning place and reflects the fact that isotopes are at the same place on the periodic table. Today more than 2200 isotopes of the 92 naturally occurring elements are known. *Isotopes* are atoms that have the same number of protons but different numbers of neutrons. Carbon has 15 known isotopes, ranging from carbon-8 to carbon-22. Only carbon-12 and carbon-13 are stable. Carbon-14 is the longest-lived radioactive isotope. At the beginning of twentieth century detailed investigations were made of the disintegration of naturally occurring radioactive isotopes. The spontaneous disintegration of atoms is responsible for radioactivity. Those isotopes which decay (break up) in this way are said to be radioactive isotopes. Oxygen has three stable isotopes. The isotope composition of O in nature varies as a result of isotope fractionation during isotope exchange reactions, phase changes and as a result of kinetic effects.

Key words: Isotopes, Carbon and Radioisotope.

INTRODUCTION

Carbon (from Latin: *carbo* "coal") is a chemical element with symbol **C** and atomic number 6. On the periodic table, it is the first (row 2) of six elements in column (group) 14, which have in common the composition of their outer electron shell. It is nonmetallic and

tetravalent—making four electrons available to form covalent chemical bonds. There are three naturally occurring isotopes, with ^{12}C and ^{13}C being stable, while ^{14}C is radioactive, decaying with a half-life of about 5,730 years. Carbon is one of the few elements known since antiquity.
Carbon exists free in nature and has been known since prehistoric time.

Electron Configuration: $[He]2s^2 2p^2$
Word Origin: Latin *carbo*, German Kohlenstoff, French carbone: coal or charcoal

Isotopes: There are seven natural isotopes of carbon. In 1961 the International Union of Pure and Applied Chemistry adopted the isotope carbon-12 as the basis for atomic weights.

Properties: Carbon is found free in nature in three allotropic forms: amorphous (lampblack, boneblack), graphite, and diamond. A fourth form, 'white' carbon, is thought to exist. Diamond is one of the hardest substances, with a high melting point and index of refraction.

Uses: Carbon forms numerous and varied compounds with limitless applications. Many thousands of carbon compounds are integral to life processes. Diamond is prized as a gemstone and is used for cutting, drilling, and as bearings. Graphite is used as a crucible for melting metals, in pencils, for rust protection, for lubrication, and as a moderator for slowing neutrons for atomic fission. Amorphous carbon is used for removing tastes and odors.

Element Classification: Non-Metal
Density (g/cc): 2.25 (graphite)
Melting Point (K): 3820
Boiling Point (K): 5100
Appearance: dense, black (carbon black)
Atomic Volume (cc/mol): 5.3
Ionic Radius: 16 (+4e) 260 (-4e)
Specific Heat (@20°C J/g mol): 0.711
Debye Temperature (°K): 1860.00
Pauling Negativity Number: 2.55
First Ionizing Energy (kJ/mol): 1085.7
Oxidation States: 4, 2, -4
Lattice Structure: Diagonal
Lattice Constant (Å): 3.570
Crystal Structure: hexagonal
Electronegativity: 2.55 (Pauling scale)
Atomic Radius: 70 pm
Atomic Radius (calc.): 67 pm
Covalent Radius: 77 pm
Van der Waals Radius: 170 pm
Magnetic Ordering: diamagnetic
Thermal Conductivity (300 K) (graphite): (119–165) $W·m^{-1}·K^{-1}$
Thermal Conductivity (300 K) (diamond): (900–2320) $W·m^{-1}·K^{-1}$
Thermal Diffusivity (300 K) (diamond): (503–1300) mm^2/s

Mohs Hardness (graphite): 1-2
Mohs Hardness (diamond): 10.0
CAS Registry Number: 7440-44-0

Carbon (**C**) has 15 known isotopes, from ^{8}C to ^{22}C, 2 of which (^{12}C and ^{13}C) are stable. The longest-lived radioisotope is ^{14}C, with a half-life of 5,700 years. This is also the only carbon radioisotope found in nature—trace quantities are formed cosmogenically by the reaction $^{14}N + {}^{1}n \rightarrow {}^{14}C + {}^{1}H$. The most stable artificial radioisotope is ^{11}C, which has a half-life of 20.334 minutes. All other radioisotopes have half-lives under 20 seconds, most less than 200 milliseconds. The least stable isotope is ^{8}C, with a half-life of 2.0 x 10^{-21} s. Averaging over natural abundances, the relative atomic mass for carbon is 12.0107 (*de Laeter et al., 2003*).

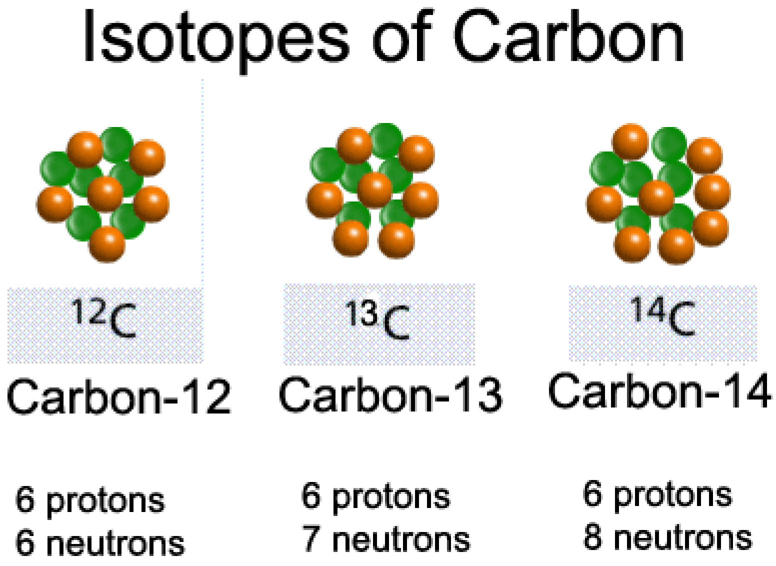

Figure 1. Show Isotopes of carbon.

Natural isotopes

Carbon-12, Carbon-13 and Carbon-14

There are three naturally occurring isotopes of carbon: 12, 13, and 14. ^{12}C and ^{13}C are stable, occurring in a natural proportion of approximately 99:1. ^{14}C is produced by thermal neutrons from cosmic radiation in the upper atmosphere, and is transported down to earth to be absorbed by living biological material. Isotopically, ^{14}C constitutes a negligible part; but, since it is radioactive with a half-life of 5,700 years, it is radiometrically detectable. Since dead tissue doesn't absorb ^{14}C, the amount of ^{14}C is one of the methods used within the field of archeology for radiometric dating of biological material (Audi et al., 2003).

Paleoclimate

^{12}C and ^{13}C are measured as the isotope ratio $\delta^{13}C$ in benthic foraminifera and used as a proxy for nutrient cycling and the temperature dependent air-sea exchange of CO_2 (ventilation). Plants find it easier to use the lighter isotopes (^{12}C) when they convert sunlight and carbon dioxide into food. So, for example, large blooms of plankton (free-floating organisms) absorb large amounts of ^{12}C from the oceans. Originally, the ^{12}C was mostly incorporated into the seawater from the atmosphere. If the oceans that the plankton live in are stratified (meaning that there are layers of warm water near the top, and colder water deeper down), then the surface water does not mix very much with the deeper waters, so that when the plankton dies, it sinks and takes away ^{12}C from the surface, leaving the surface layers relatively rich in ^{13}C. Where cold waters well up from the depths (such as in the North Atlantic), the water carries ^{12}C back up with it. So, when the ocean was less stratified than today, there was much more ^{12}C in the skeletons of surface-dwelling species. Other indicators of past climate include the presence of tropical species, coral growths rings, etc. [*The weather makers*]

Cosmogenic Isotop

Cosmogenic nuclides (or **cosmogenic isotopes**) are rare isotopes created when a high-energy cosmic ray interacts with the nucleus of an *in situ* Solar System atom, causing cosmic ray spallation. These isotopes are produced within Earth materials such as rocks or soil, in Earth's atmosphere, and in extraterrestrial items such as meteorites. By measuring cosmogenic isotopes, scientists are able to gain insight into a range of geological and astronomical processes. There are both radioactive and stable cosmogenic isotopes. Some of these radioisotopes are tritium, carbon-14 and phosphorus-32 (Holden, 2004).

Table 1. Isotopes of the chemical elements.

V·T·E· Isotopes of the chemical elements

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	**	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
	*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
	**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

Table of nuclides · Categories: Isotopes · Tables of nuclides · Metastable isotopes · Isotopes by element ·

Categories: Carbon | Isotopes of carbon | Lists of isotopes by element

Certain light (low atomic number) primordial nuclides (some isotopes of lithium, beryllium and boron) are thought to have arisen not only during the Big Bang, and also (and perhaps primarily) to have been made after the Big Bang, but before the condensation of the Solar System, by the process of cosmic ray spallation on interstellar gas and dust. This explains their higher abundance in cosmic rays as compared with their ratios and abundances of certain other nuclides on Earth. However, the arbitrary defining qualification for cosmogenic nuclides of being formed "in situ in the Solar System" (meaning inside an already-aggregated piece of the Solar System) prevents primordial nuclides formed by cosmic ray spallation *before* the formation of the Solar System, from being termed "cosmogenic nuclides"— even though the mechanism for their formation is exactly the same. These same nuclides still arrive on Earth in small amounts in cosmic rays, and are formed in meteoroids, in the atmosphere, on Earth, "cosmogenically." However, beryllium (all of it stable beryllium-9) is present primordially in the Solar System in much larger amounts, having existed prior to the condensation of the Solar System, and thus present in the materials from which the Solar System formed.

Table 2. Show table of isotopes.

S.No	Isotopes	Symbol
1	Uranium isotopes	^{232}U, ^{238}U, ^{235}U
2	Nitrogen isotopes	^{14}N, ^{15}N
3	Chlorine isotopes	^{35}Cl, ^{36}Cl, ^{37}Cl
4	Copper isotopes	^{63}Cu, ^{65}Cu
5	Helium isotopes	^{3}He, ^{4}He
6	Bromine isotopes	^{79}Br, ^{81}Br
7	Sulfur isotopes	^{32}S, ^{33}S, ^{34}S, ^{36}S
8	Lithium isotopes	^{6}Li, ^{7}Li, ^{8}Li
9	Potassium isotopes	^{39}P, ^{40}P, ^{41}P
10	Iron isotopes	^{54}Fe, ^{56}Fe, ^{57}Fe, ^{58}Fe
11	Boron isotopes	^{10}B, ^{11}B
12	Calcium isotopes	^{40}Ca, ^{42}Ca, ^{43}Ca, ^{44}Ca, ^{46}Ca
13	Sodium isotopes	^{22}Na, ^{24}Na
14	Neon isotopes	^{20}Ne, ^{21}Ne, ^{22} Ne
15	Iodine isotopes	^{127}I, ^{129}I
16	Phosphorus isotopes	^{32}P
17	Fluorine isotopes	^{19}F
18	Aluminum isotopes	^{26}Al, ^{27}Al
19	Silicon isotopes	^{28}Si, ^{29}Si, ^{30}Si, ^{32}Si
20	Gold isotopes	^{197}Au
21	Isotopes of magnesium	^{24}Mg, ^{25}Mg, ^{26}Mg

To make the distinction in another fashion, the *timing* of their formation determines which subset of cosmic ray spallation-produced nuclides are termed **primordial** or **cosmogenic** (a nuclide cannot belong to both classes). By convention, certain stable nuclides of lithium, beryllium, and boron are thought to have been produced by cosmic ray spallation in the period of time *between* the Big Bang and the Solar System's formation (thus making these primordial nuclides, by definition) are not termed "cosmogenic," even though they were formed by the same process as the cosmogenic nuclides (although at an earlier time). The primordial nuclide beryllium-9, the only stable beryllium isotope, is an example of this type of nuclide (Wieser, 2006).

In contrast, even though the radioactive isotopes beryllium-7 and beryllium-10 fall into this series of three light elements (lithium, beryllium, boron) formed mostly by cosmic ray spallation nucleosynthesis, both of these nuclides have half lives too short for them to have been formed before the formation of the Solar System, and thus they cannot be primordial nuclides. Since the cosmic ray spallation route is the only possible source of beryllium-7 and beryllium-10 occurrence naturally in the environment, they are therefore cosmogenic (Campbell et al. 1967).

Tracing food sources and diets

The quantities of the different isotopes can be measured by mass spectrometry and compared to a standard; the result (e.g. the delta of the $^{13}C = \delta^{13}C$) is expressed as parts per thousand (‰).

$$\delta^{13}C = \left(\frac{\left(\frac{^{13}C}{^{12}C}\right)_{sample}}{\left(\frac{^{13}C}{^{12}C}\right)_{standard}} - 1 \right) * 1000\ ‰$$

Stable carbon isotopes in carbon dioxide are utilized differentially by plants during photosynthesis. Grasses in temperate climates (barley, rice, wheat, rye and oats, plus sunflower, potato, tomatoes, peanuts, cotton, sugar beet, and most trees and their nuts/fruits, roses and Kentucky bluegrass) follow a C3 photosynthetic pathway that will yield $\delta^{13}C$ values averaging about −26.5‰. Grasses in hot arid climates (maize in particular, but also millet, sorghum, sugar cane and crabgrass) follow a C4 photosynthetic pathway that produces $\delta^{13}C$ values averaging about −12.5‰. It follows that eating these different plants will affect the $\delta^{13}C$ values in the consumer's body tissues. If an animal (or human) eats only C3 plants, their $\delta^{13}C$ values will be from −18.5 to −22.0‰ in their bone collagen and −14.5‰ in their apatite. [Tycot, 2004]

In contrast, C4 feeders will have bone collagen with a value of −7.5‰ and apatite value of −0.5‰.In actual case studies, millet and maize eaters can easily be distinguished from rice and wheat eaters. Studying how these dietary preferences are distributed geographically through time can illuminate migration paths of people and dispersal paths of different agricultural crops. However, human groups have often mixed C3 and C4 plants (northern Chinese historically subsisted on wheat and millet), or mixed plant and animal groups together (for example, southeastern Chinese subsisting on rice and fish). [Hedges Richard (2006)]

1. Bold for stable isotopes
2. Subsequently decays by double proton emission to $\mathbf{^{4}He}$ for a net reaction of ^{8}C -> $\mathbf{^{4}He}$ + 4$\mathbf{^{1}H}$
3. Immediately decays by proton emission to ^{8}Be, which immediately decays to two $\mathbf{^{4}He}$ atoms for a net reaction of ^{9}C -> 2$\mathbf{^{4}He}$ + $\mathbf{^{1}H}$ + e^{+}
4. Immediately decays into two $\mathbf{^{4}He}$ atoms for a net reaction of ^{9}C -> 2$\mathbf{^{4}He}$ + $\mathbf{^{1}H}$ + e^{+}
5. Immediately decays by proton emission to $\mathbf{^{4}He}$ for a net reaction of ^{9}C -> 2$\mathbf{^{4}He}$ + $\mathbf{^{1}H}$ + e^{+}
6. Used for labeling molecules in PET scans
7. **^**The unified atomic mass unit is defined as 1/12 the mass of an unbound atom of carbon-12 at ground state
8. Ratio of ^{12}C to ^{13}C used to measure biological productivity in ancient times and differing types of photosynthesis
9. Has an important use in radiodating (see carbon dating)
10. Primarily cosmogenic, produced by neutrons striking atoms of ^{14}N (^{14}N + ^{1}n -> ^{14}C + ^{1}H)
11. Has 1 halo neutron

12. Has 2 halo neutrons

- The precision of the isotope abundances and atomic mass is limited through variations. The given ranges should be applicable to any normal terrestrial material.
- Values marked # are not purely derived from experimental data, but at least partly from systematic trends. Spins with weak assignment arguments are enclosed in parentheses.
- Uncertainties are given in concise form in parentheses after the corresponding last digits. Uncertainty values denote one standard deviation, except isotopic composition and standard atomic mass from IUPAC, which use expanded uncertainties.
- Carbon-12 nuclide is of particular importance as it is used as the standard from which atomic masses of all nuclides are expressed: its atomic mass is by definition 12 Da.
- Nuclide masses are given by IUPAP Commission on Symbols, Units, Nomenclature, Atomic Masses and Fundamental Constants (SUNAMCO).
- Isotope abundances are given by IUPAC Commission on Isotopic Abundances and Atomic Weights.

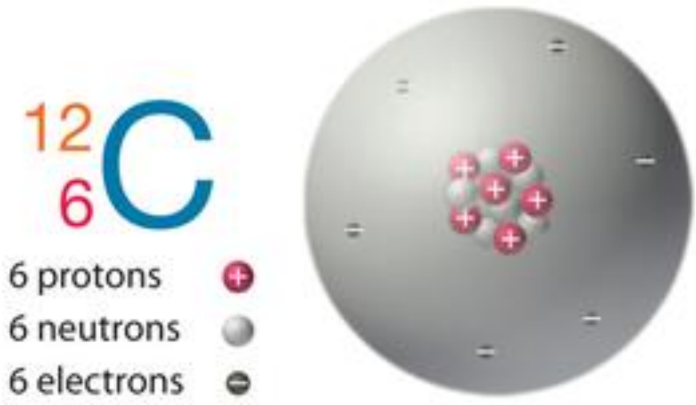

Figure 2. Number protos, neutrons and electrons in Carbon.

Significance of Isotopes

While discovered less than 100 years ago, Isotopes are now used in a wide variety of scientific applications that touch the lives of almost every citizen. These include: Radiopharmaceuticals used for medical imaging in the diagnosis of a wide range of ailments, from pneumonia to heart problems to cancer; Radiopharmaceuticals for cancer treatment and other therapeutic applications; Smoke detectors used in our home and offices; Batteries that power NASA satellites in the far reaches of our solar system; Control rods that prevent nuclear power reactors from melting down; As a ''fingerprint'' used in forensic analysis of food preparation sites and techniques; To calibrate detectors used to keep our shipping ports safe from nuclear terrorism; to enable new sources of energy such as nuclear fusion; and many other applications in energy production, industrial diagnostic methods, archeology, geology, ecology, astronomy, and physics.

There are 90 naturally occurring elements with roughly 250 stable isotopes, and over 3200 unstable or radioactive isotopes. Different isotopes of the same element often have completely different properties -- making some of them invaluable for mankind, and others worthless [for the time being]. The production of separated isotopic samples -- whereby the purity of one isotope is greatly enhanced over its natural abundance -- can be very time consuming and expensive, and supplying the amounts needed for the growing demand in the above applications is a tremendous challenge. One of the most important and compelling utilization of radioisotopes is for medical procedures, both for diagnostics and treatment. While the NIDC is not directly involved in this work, many of the radioisotopes that we manage are primarily used in these critical applications.

The presentations below give overall background information on medical uses as well as some more specific information on Tc-99m and on isotopes for Positron Emission Tomography (PET) procedures. Technetium-99m is used in roughly 30 million medical imaging procedures a year -- roughly one per second -- making it the most extensively used radioisotope for medical diagnostics. It can be used for imaging a variety of ailments such as impeded blood flow to the heart and the spread of cancer to bones. Because of the demand and because the half-life is only 6 hours, fresh batches of the parent isotope Molybdenum-99 must be continually produced to satisfy worldwide demand.

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