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Radionuclides-Basics, Applications and Significance

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ABSTRACT: A radionuclide (radioactive nuclide, radioisotope or radioactive isotope) is a nuclide that has excess nuclear energy, making it unstable. This excess energy can be used in one of three ways: emitted from the nucleus as gamma radiation; transferred to one of its electrons to release it as a conversion electron; or used to create and emit a new particle (alpha particle or beta particle) from the nucleus. During those processes, the radionuclide is said to undergo radioactive decay. These emissions are considered ionizing radiation because they are energetic enough to liberate an electron from another atom. The radioactive decay can produce a stable nuclide or will sometimes produce a new unstable radionuclide which may undergo further decay. Radioactive decay is a random process at the level of single atoms: it is impossible to predict when one particular atom will decay. However, for a collection of atoms of a single nuclide the decay rate, and thus the half-life (t1/2) for that collection, can be calculated from their measured decay constants. The range of the half-lives of radioactive atoms has no known limits and spans a time range of over 55 orders of magnitude.

KEYWORDS: radionuclides, radioisotope, decay, magnitude, radiation, half-lives, electron, nucleus

I.INTRODUCTION

Radionuclides occur naturally or are artificially produced in nuclear reactors, cyclotrons, particle accelerators or radionuclide generators. There are about 730 radionuclides with half-lives longer than 60 minutes (see list of nuclides). Thirty-two of those are primordial radionuclides that were created before the earth was formed. At least another 60 radionuclides are detectable in nature, either as daughters of primordial radionuclides or as radionuclides produced through natural production on Earth by cosmic radiation. More than 2400 radionuclides have half-lives less than 60 minutes. Most of those are only produced artificially, and have very short half-lives. For comparison, there are about 251 stable nuclides. (In theory, only 146 of them are stable, and the other 105 are believed to decay via alpha decay, beta decay, double beta decay, electron capture, or double electron capture.)[1]

All chemical elements can exist as radionuclides. Even the lightest element, hydrogen, has a well-known radionuclide, tritium. Elements heavier than lead, and the elements technetium and promethium, exist only as radionuclides.[2] (In theory, elements heavier than dysprosium exist only as radionuclides, but some such elements, like gold and platinum, are observationally stable and their half-lives have not been determined).[3]

Unplanned exposure to radionuclides generally has a harmful effect on living organisms including humans, although low levels of exposure occur naturally without harm. The degree of harm will depend on the nature and extent of the radiation produced, the amount and nature of exposure (close contact, inhalation or ingestion), and the biochemical properties of the element; with increased risk of cancer the most usual consequence. [4] However, radionuclides with suitable properties are used in nuclear medicine for both diagnosis and treatment. An imaging tracer made with radionuclides is called a radioactive tracer. A pharmaceutical drug made with radionuclides is called a radiopharmaceutical.

On Earth, naturally occurring radionuclides fall into three categories: primordial radionuclides, secondary radionuclides, and cosmogenic radionuclides.[5]

- Radionuclides are produced in stellar nucleosynthesis and supernova explosions along with stable nuclides. Most decay quickly but can still be observed astronomically and can play a part in understanding astronomic processes. Primordial radionuclides, such as uranium and thorium, exist in the present time because their half-lives are so long (>100 million years) that they have not yet completely decayed. Some radionuclides have half-lives so long

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(many times the age of the universe) that decay has only recently been detected, and for most practical purposes they can be considered stable, most notably bismuth-209: detection of this decay meant that bismuth was no longer considered stable. It is possible decay may be observed in other nuclides, adding to this list of primordial radionuclides.

- Secondary radionuclides are radiogenic isotopes derived from the decay of primordial radionuclides. They have shorter half-lives than primordial radionuclides. They arise in the decay chain of the primordial isotopes thorium-232, uranium-238, and uranium-235. Examples include the natural isotopes of polonium and radium.[6]
- Cosmogenic isotopes, such as carbon-14, are present because they are continually being formed in the atmosphere due to cosmic rays.[6]

Many of these radionuclides exist only in trace amounts in nature, including all cosmogenic nuclides. Secondary radionuclides will occur in proportion to their half-lives, so short-lived ones will be very rare. For example, polonium can be found in uranium ores at about 0.1 mg per metric ton (1 part in 10^{10}).[7][8] Further radionuclides may occur in nature in virtually undetectable amounts as a result of rare events such as spontaneous fission or uncommon cosmic ray interactions.[7]

Radionuclides are produced as an unavoidable result of nuclear fission and thermonuclear explosions. The process of nuclear fission creates a wide range of fission products, most of which are radionuclides. Further radionuclides can be created from irradiation of the nuclear fuel (creating a range of actinides) and of the surrounding structures, yielding activation products. This complex mixture of radionuclides with different chemistries and radioactivity makes handling nuclear waste and dealing with nuclear fallout particularly problematic. Synthetic radionuclides are deliberately synthesised using nuclear reactors, particle accelerators or radionuclide generators:

- As well as being extracted from nuclear waste, radioisotopes can be produced deliberately with nuclear reactors, exploiting the high flux of neutrons present. These neutrons activate elements placed within the reactor. A typical product from a nuclear reactor is iridium-192. The elements that have a large propensity to take up the neutrons in the reactor are said to have a high neutron cross-section.
- Particle accelerators such as cyclotrons accelerate particles to bombard a target to produce radionuclides. Cyclotrons accelerate protons at a target to produce positron-emitting radionuclides, e.g. fluorine-18.[8]
- Radionuclide generators contain a parent radionuclide that decays to produce a radioactive daughter. The parent is usually produced in a nuclear reactor. A typical example is the technetium-99m generator used in nuclear medicine. The parent produced in the reactor is molybdenum-99.

Radionuclides are used in two major ways: either for their radiation alone (irradiation, nuclear batteries) or for the combination of chemical properties and their radiation (tracers, biopharmaceuticals).[9]

- In biology, radionuclides of carbon can serve as radioactive tracers because they are chemically very similar to the nonradioactive nuclides, so most chemical, biological, and ecological processes treat them in a nearly identical way. One can then examine the result with a radiation detector, such as a Geiger counter, to determine where the provided atoms were incorporated. For example, one might culture plants in an environment in which the carbon dioxide contained radioactive carbon; then the parts of the plant that incorporate atmospheric carbon would be radioactive. Radionuclides can be used to monitor processes such as DNA replication or amino acid transport.
- in physics and biology radionuclide X-ray fluorescence spectrometry is used to determine chemical composition of the compound. Radiation from a radionuclide source hits the sample and excites characteristic X-rays in the sample. This radiation is registered and the chemical composition of the sample can be determined from the analysis of the measured spectrum. By measuring the energy of the characteristic radiation lines, it is possible to determine the proton number of the chemical element that emits the radiation, and by measuring the number of emitted photons, it is possible to determine the concentration of individual chemical elements.[10]
- In nuclear medicine, radioisotopes are used for diagnosis, treatment, and research. Radioactive chemical tracers emitting gamma rays or positrons can provide diagnostic information about internal anatomy and the functioning of specific organs, including the human brain.[9][10][11] This is used in some forms of tomography: single-photon emission computed tomography and positron emission tomography (PET) scanning and Cherenkov luminescence

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imaging. Radioisotopes are also a method of treatment in hemopoietic forms of tumors; the success for treatment of solid tumors has been limited. More powerful gamma sources sterilise syringes and other medical equipment.

- In food preservation, radiation is used to stop the sprouting of root crops after harvesting, to kill parasites and pests, and to control the ripening of stored fruit and vegetables. Food irradiation usually uses beta-decaying nuclides with strong gamma emissions like Cobalt-60 or Caesium-137.[11]
- In industry, and in mining, radionuclides are used to examine welds, to detect leaks, to study the rate of wear, erosion and corrosion of metals, and for on-stream analysis of a wide range of minerals and fuels.
- In spacecraft, radionuclides are used to provide power and heat, notably through radioisotope thermoelectric generators (RTGs) and radioisotope heater units (RHUs).
- In astronomy and cosmology, radionuclides play a role in understanding stellar and planetary process.[12]
- In particle physics, radionuclides help discover new physics (physics beyond the Standard Model) by measuring the energy and momentum of their beta decay products (for example, neutrinoless double beta decay and the search for weakly interacting massive particles).[12]
- In ecology, radionuclides are used to trace and analyze pollutants, to study the movement of surface water, and to measure water runoffs from rain and snow, as well as the flow rates of streams and rivers.
- In geology, archaeology, and paleontology, natural radionuclides are used to measure ages of rocks, minerals, and fossil materials.[13]

II.DISCUSSION

The following table lists properties of selected radionuclides illustrating the range of properties and uses.

Isotope	Z	N	half-life	DM	DE keV	Mode of formation	Comments
Tritium (^{3}H)	1	2	12.3 y	β^-	19	Cosmogenic	lightest radionuclide, used in artificial nuclear fusion, also used for radioluminescence and as oceanic transient tracer. Synthesized from neutron bombardment of lithium-6 or deuterium
Beryllium-10	4	6	1,387,000 y	β^-	556	Cosmogenic	used to examine soil erosion, soil formation from regolith, and the age of ice cores
Carbon-14	6	8	5,700 y	β^-	156	Cosmogenic	used for radiocarbon dating
Fluorine-18	9	9	110 min	β^+, EC	633/1655	Cosmogenic	positron source, synthesised for use as a medical radiotracer in PET scans.
Aluminium-26	13	13	717,000 y	β^+, EC	4004	Cosmogenic	exposure dating of rocks, sediment
Chlorine-36	17	19	301,000 y	β^-, EC	709	Cosmogenic	exposure dating of rocks, groundwater tracer
Potassium-40	19	21	1.24×10^{9} y	β^-, EC	1330 /1505	Primordial	used for potassium-argon dating, source of atmospheric argon, source of radiogenic heat, largest source of natural radioactivity
Calcium-41	20	21	99,400 y	EC		Cosmogenic	exposure dating of carbonate rocks
Cobalt-60	27	33	5.3 y	β^-	2824	Synthetic	produces high energy gamma rays, used for radiotherapy, equipment sterilisation, food irradiation
Krypton-81	36	45	229,000 y	β^+		Cosmogenic	groundwater dating

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Isotope	Z	N	half-life	DM	DE keV	Mode of formation	Comments
Strontium-90	38	52	28.8 y	β^-	546	Fission product	medium-lived fission product; probably most dangerous component of nuclear fallout
Technetium-99	43	56	210,000 y	β^-	294	Fission product	most common isotope of the lightest unstable element, most significant of long-lived fission products
Technetium-99m	43	56	6 hr	γ,IC	141	Synthetic	most commonly used medical radioisotope, used as a radioactive tracer
Iodine-129	53	76	15,700,000 y	β^-	194	Cosmogenic	longest lived fission product; groundwater tracer
Iodine-131	53	78	8 d	β^-	971	Fission product	most significant short-term health hazard from nuclear fission, used in nuclear medicine, industrial tracer
Xenon-135	54	81	9.1 h	β^-	1160	Fission product	strongest known "nuclear poison" (neutron-absorber), with a major effect on nuclear reactor operation.
Caesium-137	55	82	30.2 y	β^-	1176	Fission product	other major medium-lived fission product of concern
Gadolinium-153	64	89	240 d	EC		Synthetic	Calibrating nuclear equipment, bone density screening
Bismuth-209	83	126	2.01×10^{19}y	α	3137	Primordial	long considered stable, decay only detected in 2003
Polonium-210	84	126	138 d	α	5307	Decay product	Highly toxic, used in poisoning of Alexander Litvinenko
Radon-222	86	136	3.8 d	α	5590	Decay product	gas, responsible for the majority of public exposure to ionizing radiation, second most frequent cause of lung cancer
Thorium-232	90	142	1.4×10^{10} y	α	4083	Primordial	basis of thorium fuel cycle
Uranium-235	92	143	7×10^{8}y	α	4679	Primordial	fissile, main nuclear fuel
Uranium-238	92	146	4.5×10^{9} y	α	4267	Primordial	Main Uranium isotope
Plutonium-238	94	144	87.7 y	α	5593	Synthetic	used in radioisotope thermoelectric generators (RTGs) and radioisotope heater units as an energy source for spacecraft
Plutonium-239	94	145	24,110 y	α	5245	Synthetic	used for most modern nuclear weapons
Americium-241	95	146	432 y	α	5486	Synthetic	used in household smoke detectors as an ionising agent
Californium-252	98	154	2.64 y	α/SF	6217	Synthetic	undergoes spontaneous fission (3% of decays), making it a powerful neutron source, used as a reactor initiator and for

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Isotope	Z	N	half-life	DM	DE keV	Mode of formation	Comments
							detection devices

Key: Z = atomic number; N = neutron number; DM = decay mode; DE = decay energy; EC = electron capture

Radionuclides are present in many homes as they are used inside the most common household smoke detectors. The radionuclide used is americium-241, which is created by bombarding plutonium with neutrons in a nuclear reactor. It decays by emitting alpha particles and gamma radiation to become neptunium-237. Smoke detectors use a very small quantity of ^{241}Am (about 0.29 micrograms per smoke detector) in the form of americium dioxide. ^{241}Am is used as it emits alpha particles which ionize the air in the detector's ionization chamber. A small electric voltage is applied to the ionized air which gives rise to a small electric current. In the presence of smoke, some of the ions are neutralized, thereby decreasing the current, which activates the detector's alarm.[13][14]

Radionuclides that find their way into the environment may cause harmful effects as radioactive contamination. They can also cause damage if they are excessively used during treatment or in other ways exposed to living beings, by radiation poisoning. Potential health damage from exposure to radionuclides depends on a number of factors, and "can damage the functions of healthy tissue/organs. Radiation exposure can produce effects ranging from skin redness and hair loss, to radiation burns and acute radiation syndrome. Prolonged exposure can lead to cells being damaged and in turn lead to cancer. Signs of cancerous cells might not show up until years, or even decades, after exposure."[15]

III.RESULTS

Following is a summary table for the list of 989 nuclides with half-lives greater than one hour. A total of 251 nuclides have never been observed to decay, and are classically considered stable. Of these, 90 are believed to be absolutely stable except to proton decay (which has never been observed), while the rest are "observationally stable" and theoretically can undergo radioactive decay with extremely long half-lives.[14]

The remaining tabulated radionuclides have half-lives longer than 1 hour, and are well-characterized (see list of nuclides for a complete tabulation). They include 30 nuclides with measured half-lives longer than the estimated age of the universe (13.8 billion years[16]), and another four nuclides with half-lives long enough (> 100 million years) that they are radioactive primordial nuclides, and may be detected on Earth, having survived from their presence in interstellar dust since before the formation of the solar system, about 4.6 billion years ago. Another 60+ short-lived nuclides can be detected naturally as daughters of longer-lived nuclides or cosmic-ray products. The remaining known nuclides are known solely from artificial nuclear transmutation.

Numbers are not exact, and may change slightly in the future, as "stable nuclides" are observed to be radioactive with very long half-lives.[15]

This is a summary table for the 989 nuclides with half-lives longer than one hour (including those that are stable), given in list of nuclides.

Stability class	Number of nuclides	Running total	Notes on running total
Theoretically stable to all but proton decay	90	90	Includes first 40 elements. Proton decay yet to be observed.
Theoretically stable to alpha decay, beta decay, isomeric transition, and double beta decay but not spontaneous fission, which is	56	146	All nuclides that are possibly completely stable (spontaneous fission has never been observed for nuclides with mass number <

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Stability class	Number of nuclides	Running total	Notes on running total
possible for "stable" nuclides ≥ niobium-93			232).
Energetically unstable to one or more known decay modes, but no decay yet seen. All considered "stable" until decay detected.	106	251	Total of classically stable nuclides.
Radioactive primordial nuclides.	35	286	Total primordial elements include uranium, thorium, bismuth, rubidium-87, potassium-40, tellurium-128 plus all stable nuclides.
Radioactive nonprimordial, but naturally occurring on Earth.	61	347	Carbon-14 (and other isotopes generated by cosmic rays) and daughters of radioactive primordial elements, such as radium, polonium, etc. 41 of these have a half life of greater than one hour.
Radioactive synthetic half-life ≥ 1.0 hour). Includes most useful radiotracers.	662	989	These 989 nuclides are listed in the article List of nuclides.
Radioactive synthetic (half-life < 1.0 hour).	>2400	>3300	Includes all well-characterized synthetic nuclides.

List of commercially available radionuclides

This list covers common isotopes, most of which are available in very small quantities to the general public in most countries. Others that are not publicly accessible are traded commercially in industrial, medical, and scientific fields and are subject to government regulation.[15]

Gamma emission only

Isotope	Activity	Half-life	Energies (keV)
Barium-133	9694 TBq/kg (262 Ci/g)	10.7 years	81.0, 356.0

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Cadmium-109	96200 TBq/kg (2600 Ci/g)	453 days	88.0
Cobalt-57	312280 TBq/kg (8440 Ci/g)	270 days	122.1
Cobalt-60	40700 TBq/kg (1100 Ci/g)	5.27 years	1173.2, 1332.5
Europium-152	6660 TBq/kg (180 Ci/g)	13.5 years	121.8, 344.3, 1408.0
Manganese-54	287120 TBq/kg (7760 Ci/g)	312 days	834.8
Sodium-22	237540 Tbq/kg (6240 Ci/g)	2.6 years	511.0, 1274.5
Zinc-65	304510 TBq/kg (8230 Ci/g)	244 days	511.0, 1115.5
Technetium-99m	1.95×10^{7} TBq/kg (5.27×10^{5} Ci/g)	6 hours	140

Beta emission only

Isotope	Activity	Half-life	Energies (keV)
Strontium-90	5180 TBq/kg (140 Ci/g)	28.5 years	546.0
Thallium-204	17057 TBq/kg (461 Ci/g)	3.78 years	763.4
Carbon-14	166.5 TBq/kg (4.5 Ci/g)	5730 years	49.5 (average)
Tritium (Hydrogen-3)	357050 TBq/kg (9650 Ci/g)	12.32 years	5.7 (average)

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Alpha emission only

Isotope	Activity	Half-life	Energies (keV)
Polonium-210	166500 TBq/kg (4500 Ci/g)	138.376 days	5304.5
Uranium-238	12580 kBq/kg (0.00000034 Ci/g)	4.468 billion years	4267

Multiple radiation emitters

Isotope	Activity	Half-life	Radiation types	Energies (keV)
Caesium-137	3256 TBq/kg (88 Ci/g)	30.1 years	Gamma & beta	G: 32, 661.6 B: 511.6, 1173.2
Americium-241	129.5 TBq/kg (3.5 Ci/g)	432.2 years	Gamma & alpha	G: 59.5, 26.3, 13.9 A: 5485, 5443

Radiometric dating, radioactive dating or radioisotope dating is a technique which is used to date materials such as rocks or carbon, in which trace radioactive impurities were selectively incorporated when they were formed. The method compares the abundance of a naturally occurring radioactive isotope within the material to the abundance of its decay products, which form at a known constant rate of decay.[1] The use of radiometric dating was first published in 1907 by Bertram Boltwood[2] and is now the principal source of information about the absolute age of rocks and other geological features, including the age of fossilized life forms or the age of Earth itself, and can also be used to date a wide range of natural and man-made materials.

Together with stratigraphic principles, radiometric dating methods are used in geochronology to establish the geologic time scale.[3] Among the best-known techniques are radiocarbon dating, potassium–argon dating and uranium–lead dating. By allowing the establishment of geological timescales, it provides a significant source of information about the ages of fossils and the deduced rates of evolutionary change. Radiometric dating is also used to date archaeological materials, including ancient artifacts.[16]

Different methods of radiometric dating vary in the timescale over which they are accurate and the materials to which they can be applied.

IV.CONCLUSIONS

All ordinary matter is made up of combinations of chemical elements, each with its own atomic number, indicating the number of protons in the atomic nucleus. Additionally, elements may exist in different isotopes, with each isotope of an element differing in the number of neutrons in the nucleus. A particular isotope of a particular element is called a nuclide. Some nuclides are inherently unstable. That is, at some point in time, an atom of such a nuclide will undergo radioactive decay and spontaneously transform into a different nuclide. This transformation may be accomplished in a number of different ways, including alpha decay (emission of alpha particles) and beta decay (electron emission, positron emission, or electron capture). Another possibility is spontaneous fission into two or more nuclides. While the moment in time at which a particular nucleus decays is unpredictable, a collection of atoms of a radioactive nuclide decays exponentially at a rate described by a parameter known as the half-life, usually given in units of years when discussing dating techniques. After one half-life has elapsed, one half of the atoms of the nuclide in question will have decayed into a "daughter" nuclide or decay product. In many cases, the daughter nuclide itself is radioactive, resulting in a decay chain, eventually ending with the formation of a stable (nonradioactive) daughter

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nuclide; each step in such a chain is characterized by a distinct half-life. In these cases, usually the half-life of interest in radiometric dating is the longest one in the chain, which is the rate-limiting factor in the ultimate transformation of the radioactive nuclide into its stable daughter. Isotopic systems that have been exploited for radiometric dating have half-lives ranging from only about 10 years (e.g., tritium) to over 100 billion years (e.g., samarium-147).[4]

For most radioactive nuclides, the half-life depends solely on nuclear properties and is essentially constant.[5] This is known because decay constants measured by different techniques give consistent values within analytical errors and the ages of the same materials are consistent from one method to another. It is not affected by external factors such as temperature, pressure, chemical environment, or presence of a magnetic or electric field.[6][7][8] The only exceptions are nuclides that decay by the process of electron capture, such as beryllium-7, strontium-85, and zirconium-89, whose decay rate may be affected by local electron density. For all other nuclides, the proportion of the original nuclide to its decay products changes in a predictable way as the original nuclide decays over time. This predictability allows the relative abundances of related nuclides to be used as a clock to measure the time from the incorporation of the original nuclides into a material to the present.[17]

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