Types of Radioactivity: Alpha, Beta, and Gamma Decay by Prof. Dr MAHMOUD NAJIM 2020

The first radiation sources were natural radio nuclides, such as ^{222}Rn and ^{210}PO, which were incorporated into the medium to be investigated or used as external irradiators, e.g., ^{226}Ra. Later, artificial radio nuclides, and in particular ^{60}Co, were commonly used in radiation chemistry.

Radiochemistry is concerned in all its aspects and objectives with radioactivity, including decay and the emission of radiations.

Main topics of radiochemistry include the following:

1. The physicochemical properties at very low concentration of all elements for which a suitable radioactive isotope with high specific activity is available.

2. The physicochemical properties of radio elements for which the longest lived isotope is available only at the tracer scale level.

3. The chemical consequences, both atomic and molecular of nuclear transformations which include change in the structure of solids and in the properties of the species formed in radioactive decays and in nuclear reactions

4. The relation between nuclear and chemical properties, in particular the modification of certain nuclear properties in relation to the chemical environment.

5. Properties of radio elements available in weighable quantities, but with very high specific activity.

Radiochemistry and periodic table of the elements:

Most of the elements in the periodic chart are of importance to radiochemistry. These include:

1. The numerous elements for which a short-lived radioisotope is available.

2. The radioactive fission products from binary fission, which are isotopes of 35 elements comprised between Zn and Tb, and tritium, the radioactive hydrogen isotope, resulting from ternary fission.

3. All radio elements, i.e., the elements which have no stable isotopes. Several of these have only short-lived isotopes and thus exist only in non ponder able amounts; examples are Po, At, Rn, Fr, and all radio elements from Z = 99 to Z = 109, the present limit. Some radio elements in macroscopic amounts have very high specific activities which perturb their chemical behavior and must be investigated at the tracer level. These include Pm, Cm, Bk, Cf, and Es. Some radio elements may possess long-lived, weighable isotopes such as ^{99}Tc and ^{231}Pa, but which are very difficult to isolate. Since Mendeleev's first attempt of classification on the basis of atomic weight and chemical similarities of the elements and their main compounds, many types of periodic tables have been proposed. The lanthanide and actinide elements are separated from the body of the table and constitute two horizontal series starting with La and Ac, respectively. The energies of the 5f and 6d orbitals, in contrast to those of the 4f and 5d orbitals, are relatively close for the early elements in the actinide series. This is reflected by delocalization of 5f electrons for the metallic elements. As a result, the 6d orbital contains one electron in Ac, is doubly occupied in Th, and then reverts to single occupation from Pa to Np. Only the next members of the series correspond electronically to the lanthanides. It follows that the chemical properties of actinides do not match those of the lanthanides. The oxidation states of the actinides are more numerous, especially as regards the earlier members Ac to Am in comparison with La to Eu. The chemical properties of

homologous elements are really similar only for the terminal groups Cm to Lr and Gd to Lu. The elements Th, Pa, and U are chemically closer to the 5d elements Hf, Ta, and W than to the lanthanides.

Radiochemistry and Chemistry:

Although chemistry has played a determinant role in nuclear science, radiochemistry, in turn, has contributed to the development of several branches of chemistry. The greatest impact was undoubtedly the completion and an extension of over 10% of Mendeleev's table of the elements. The discovery of trans uranium elements has brought a renewal to the whole field of chemistry, particularly in the inorganic sector. Investigations of the heaviest radioactive elements have provided a wealth of data, especially on the oxidation states, structure and complexation of aqua ions, and on the complexation and stability of solid compounds. This information has completed our knowledge of the trends of chemical properties of the elements within the periods and groups of the periodic table. Radiochemistry has opened the new field of chemistry at very low concentration ($< 10^{-10}$ M) that is becoming increasingly important not only for knowledge of the role and behavior of trace elements, but also in space chemistry. At the ultimate limits of concentration, radiochemistry has revealed the problem of chemistry at the level of only a few atoms. The properties of solutions at the other extreme of very high, i.e., multi molar concentrations, can in some cases be explored more conveniently with the positron probe than by classical means. Hence, radio- chemistry can furnish valuable tests of solution models both at infinite dilution and at very high concentration. The positron may be considered as a "radioactive" tracer of the electron, and in this respect has an immense potential application in all fields of chemistry. Positron chemistry proceeds at an extremely high rate and presently provides access to early events in the interaction of radiation with matter. Natural radioactive matter is omnipresent. Every part of our environment contains radio nuclides, although the activity level may be very low. However, with the present sensitivity of radiation detection and modem instrumentation, even very weak activities can be investigated.

Decay of radio elements *via* three methods :

Many nuclei are radioactive; that is, they decompose by emitting particles and in doing so, become a different nucleus. In our studies up to this point, atoms of one element were unable to change into different elements. That is because in all other types of changes we have talked about only the electrons were changing. In these changes, the nucleus, which contains the protons which dictate which element an atom is, is changing. All nuclei with 84 or more protons are radioactive and elements with less than 84 protons have both stable and unstable isotopes. All of these elements can go through nuclear changes and turn into different elements.

In natural radioactive decay, three common emissions occur. When these emissions were originally observed, scientists were unable to identify them as some already known particles and so named them

- alpha particles (α),
- beta particles, (β), and
- gamma rays (γ)

using the first three letters of the Greek alphabet. Some later time, alpha particles were identified as helium-4 nuclei, beta particles were identified as electrons, and gamma rays as a form of electromagnetic radiation like x-rays except much higher in energy and even more dangerous to living systems.

Alpha Decay

The nuclear disintegration process that emits alpha particles is called alpha decay. An example of a nucleus that undergoes alpha decay is uranium-238. The alpha decay of U-238 is

$$^{238}U_{9\,2} \rightarrow {}^{24}He_2 + {}^{234}Th_{90}$$

In this nuclear change, the uranium atom ($^{238}U_{92}$)transmuted into an atom of thorium ($^{234}Th_{90}$) and, in the process, gave off an alpha particle. Look at the symbol for the alpha particle: $^{4}He_2$. Where does an alpha particle get this symbol? The bottom number in a nuclear symbol is the number of protons. That means that the alpha particle has two protons in it which were lost by the uranium atom. The two protons also have a charge of +2. The top number, 4, is the mass number or the total of the protons and neutrons in the particle. Because it has 2 protons, and a total of 4 protons and neutrons, alpha particles must also have two neutrons. Alpha particles always have this same composition: two protons and two neutrons. Another alpha particle producer is thorium-230; $^{230}Th_{90}$ as below:

$$^{230}Th_{90} \rightarrow {}^{4}He_2 + {}^{226}Ra_{88}$$

Beta Decay

Another common decay process is beta particle emission, or beta decay. A beta particle is simply a high energy electron that is emitted from the nucleus. It may occur to you that we have a logically difficult situation here. Nuclei do not contain electrons and yet during beta decay, an electron is emitted from a nucleus. At the same time that the electron is being ejected from the nucleus, a neutron is becoming a proton. It is tempting to picture this as a neutron breaking into two pieces with the pieces being a proton and an electron. That would be convenient for simplicity, but unfortunately that is not what happens; more about this at the end of this section. For convenience sake, though, we will treat beta decay as a neutron splitting into a proton and an electron. The proton

stays in the nucleus, increasing the atomic number of the atom by one. The electron is ejected from the nucleus and is the particle of radiation called beta.

To insert an electron into a nuclear equation and have the numbers add up properly, an atomic number and a mass number had to be assigned to an electron. The mass number assigned to an electron is zero (0) which is reasonable since the mass number is the number of protons plus neutrons and an electron contains no protons and no neutrons. The atomic number assigned to an electron is negative one (-1), because that allows a nuclear equation containing an electron to balance atomic numbers. Therefore, the nuclear symbol representing an electron (beta particle) is

$$^{0}\beta_{-1}$$

Thorium-234 is a nucleus that undergoes beta decay. Here is the nuclear equation for this beta decay.

$$^{234}Th_{90} \rightarrow {}^{0}e_{-1} + {}_{91}Pa^{234}$$

As well as some nuclei decay via beta emission as below:

$$^{32}_{15}\mathrm{P} \longrightarrow {}^{32}_{16}\mathrm{S} + {}^{0}_{-1}e$$

Gamma Radiation

Frequently, gamma ray production accompanies nuclear reactions of all types. In the alpha decay of U-238, two gamma rays of different energies are emitted in addition to the alpha particle.

$$^{238}U_{92} \rightarrow {}^{4}He_{2} + {}^{234}Th_{90} + 2\,{}^{0}\gamma_{0}$$

Natural radio elements:

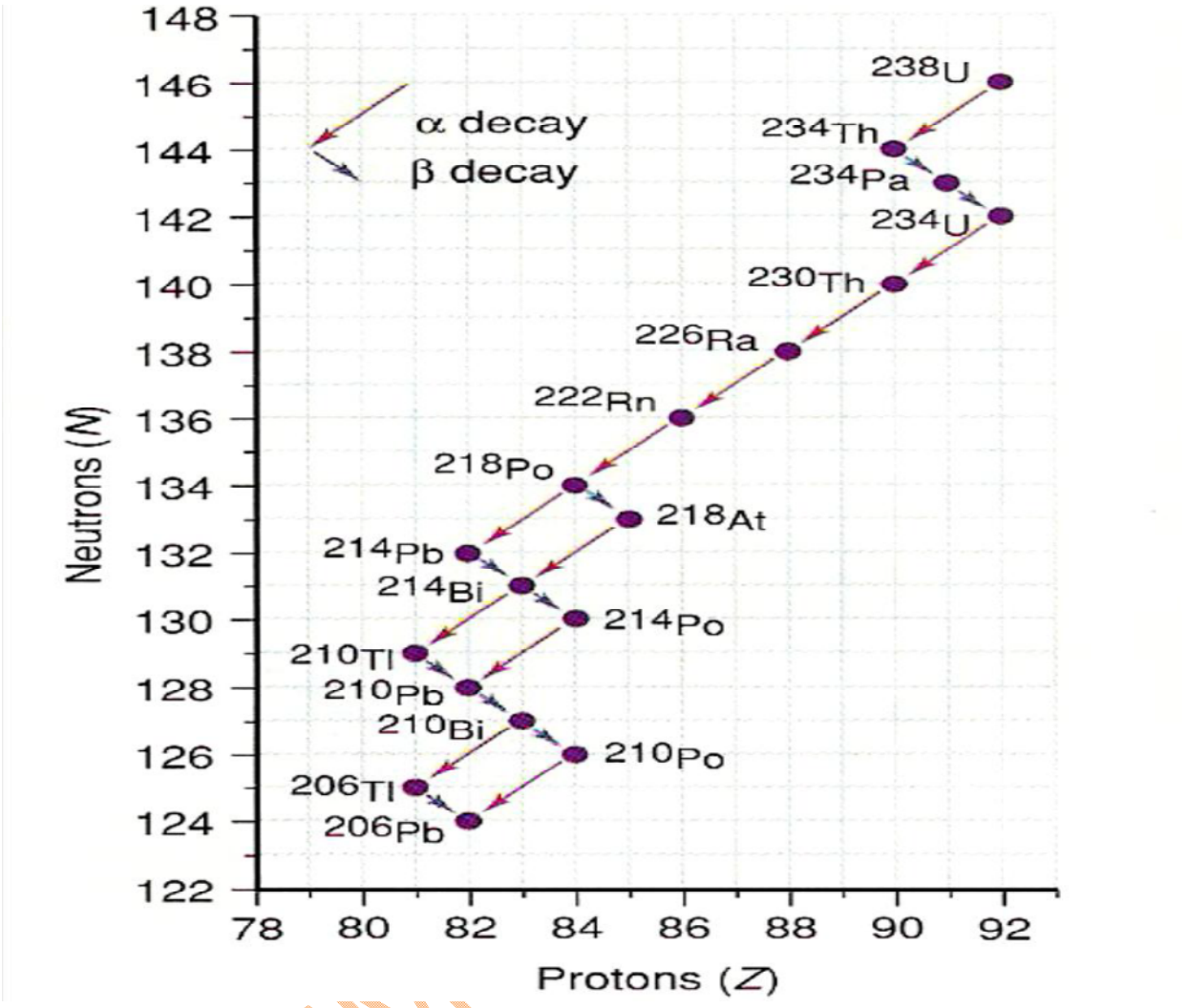
Natural radio elements are those elements present in nature that have no stable isotopes. They contribute to the environmental radioactivity and their distribution within the earth has many implications in geology and geo- chemistry. These radio elements include Po, At, Rn, Fr, Ac, Ra, Th, Pa, and U and have atomic numbers ranging from 84 to 92. Astatine is added since it is formed in rare branching of natural Po isotopes, but this radioelement is generally classed with the synthetic ones; its total amount in the earth's crust is less than 30 g. The *list deliberately does not include Tc and Pm, although these are produced in minute amounts in the spontaneous fission of uranium, nor Np and Pu found in uranium ores as the result of natural nuclear reactions; in the present context they are considered as synthetic. Heavy natural radionuclides include isotopes of the stable elements Tl, Pb, and Bi.*

Three main decay chains (or families) are observed in nature, representing three classes, and ending in three different, stable isotopes of lead (magic number). The mass number of every isotope in these chains can be represented as A = 4n, A = 4n + 2, and A = 4n + 3, respectively.

1. ^{238}U or 4n + 2 Family: The ^{238}U family ends with the stable ^{206}Pb. The longest-lived members are ^{234}U (T = 0.245 X 10^6 years), and ^{230}Th (T = 0.08 X 10^6 years.

2. ^{235}U or 4n + 3 Family: The last member of the ^{235}U family, ^{207}Pb. This family is peculiar in that it includes the three longest-lived isotopes of Pa, Ac, and Fr.

3. ^{232}Th or 4n Family: ^{232}Th leads to ^{208}Pb. The longest lived member in the family is ^{228}Ra (5.76 years, formerly called mesothoriuml).



Scheme (1). explains the radio decay of family 4n+2; $^{238}U_{92}$ series

A radioactive decay sequence (e.g. of ^{238}U) can be represented more concisely as a graph of atomic number versus neutron number.

– α decay is shown as a decrease of two protons (Z) and two neutrons (N).

– β decay is shown as a decrease of one neutron and an increase of one proton.

– Isotopes (same Z, different N) lie along vertical lines in this graph.

A radioactive isotope like ^{238}U thus generates a family of daughter isotopes in a decay series. Naturally-occurring uranium contains ^{238}U, and so will also contain components of the decay series.

Table 1 Uranium-238 Chain ^{238}U (4n+2); $^{238}U_{92}$

Nuclide	Historical Name	$T_{1/2}$	Major Radiations
^{238}U	Uranium I	4.47 × 109 y	α, < 1% γ
^{234}Th	Uranium X1	24.1 d	β,
^{234m}Pa	Uranium X2	1.17 m	β, < 1% γ
^{234}U	Uranium II	2.46 × 105 y	α, < 1% γ
^{230}Th	Ionium	7.54 × 104 y	α, < 1% γ
^{226}Ra	Radium	1600 y	α, γ
^{222}Rn	Emanation	3.82 d	α, < 1% γ
^{218}Po	Radium A	3.10 m	α, < 1% γ
^{214}Pb	Radium B	26.8 m	β, γ
^{214}Bi	Radium C	19.9 m	β, γ
^{214}Po	Radium C′	164.3 µs	α, < 1% γ
^{210}Pb	Radium D	22.3 y	β, γ
^{210}Bi	Radium E	5.01 d	B
^{210}Po	Radium F	138.4 d	α, < 1% γ
^{206}Pb	Radium G	Stable	None

Table 2. Uranium-235 Chain ^{235}U (4n+3); $^{235}U_{92}$ series

Historical Name		$T_{1/2}$	Major Radiations
^{235}U	Actinouranuim	7.04×10^8 y	α, γ
^{231}Th	Uranium Y	1.06 d	β, γ
^{231}Pa	Protoactinium	3.28 × 104 y	α, γ
Actinium		21.77 y	β, < 1% γ

Radioactinium / Actinium K		18.72 d / 22.0 m	α, γ / β, γ
^{223}Ra	Actinium X	11.44 d	α, γ
^{219}Rn	Actinon	3.96 s	α, γ
^{215}Po	Actinium A	1.78 ms	α, < 1% γ
^{211}Pb	Actinium B	36.1 m	β, γ
^{211}Bi	Actinium C	2.14 m	α, γ
^{207}Tl	Actinium C′	4.77 m	β, < 1% γ
^{207}Pb	Actinium D	Stable	None

Table 3. Thorium-238 Chain ^{232}Th (4n)' $^{232}T_{90}$ series

Nuclide	Historical Name	$T_{1/2}$	Major Radiations
^{232}Th	Thorium	1.41×10^{10} y	α, <1% γ
^{228}Ra	Mesothorium I	5.75 y	β, <1% γ
^{228}Ac	Mesothorium II	6.15 h	β, γ
^{228}Th	Radiothorium	1.91 y	α, γ
^{224}Ra	Thorium X	3.66 d	α, γ
^{220}Rn	Emanation	55.6 s	α, <1% γ
^{216}Po	Thorium A	0.145 s	α, <1% γ
^{212}Pb	Thorium B	10.64 h	β, γ
Thorium C	1.01 h		α, γ
Thorium C′ / Thorium C″	0.300 ms / 3.05 m		α / β, γ
^{208}Pb	Thorium D	Stable	Non

Natural radioactivity in the atmosphere is due mainly to the presence of one Rn isotope in each family: ^{222}Rn (the true radon, T = 3.8d), ^{220}Rn (thoron, T = 55 s) and ^{219}Rn (actinon, T = 4 s). Only the first two have lifetimes that are compatible with their release from soils and waters. The most important is 222Rn because its relatively long half-life ensures a higher steady concentration in the environment.

Artificial radio elements:

Artificial (also called synthetic or anthropogenic) radio elements are those which have no stable isotopes and do not exist in nature, or at the most only in minute amounts and often as short-lived ephemeral species. They include ^{43}Tc, ^{61}Pm, ^{85}At, and presently all elements from ^{93}Np to ^{109}Une. They are synthesized in nuclear reactions induced by neutrons for elements up to ^{99}Es and ^{100}Fm, and by charged particles for the heavier ones. In many cases these reactions lead to a mixture of isotopes of a given element for which the composition varies widely with the target, the nature and energy of the projectile, and the duration of irradiation.

All artificial radio elements with Z < 97 (except At, whose longest-lived isotope is 8.3 h ^{210}At), i.e., Tc, Pm, Np, Pu, Am, and Cm, are found in large or appreciable amounts in irradiated U or Pu fuels used in nuclear reactors. The stable end products of fission chains include potentially useful and naturally scarce elements such as Pd and Xe and most of the lanthanides. However, some of these elements contain long-lived radioisotopes such as 6.5 x 106 years for ^{107}Pd.

Radio nuclides found in nature:

Radioactive isotopes of stable elements and isotopes of radio elements are found in the environment. They result from natural nuclear reactions or from contamination due to anthropogenic activities.

1-Primary Radio nuclides:

Long-lived radio nuclides formed in the process of nucleogenesis are called primary or primordial radio nuclides. About 20 primary radio nuclides have been

recorded; they possess very long half-lives (T > 10^{10} years) and a half-lives (T > 10^{11} years). Most of them are very difficult to detect because;

(i)-the isotopic abundance is sometimes below 1%,(ii)-the half-lives are associated with low energies of the emitted α and β particles, and (iii)-the γ photons are highly converted. For these reasons the primary radio nuclides are of little concern in radiochemistry. They are even considered as stable nuclides in the isotopic *composition of* the corresponding elements. The possible occurrence of primary ^{244}Pu has already been mentioned.

2. Isotopic composition and atomic weights of primary radio nuclides and their daughters:

A consequence of existing long-lived primary radio nuclides is progressive nucleogenesis of stable elements, which started at the time of the Big Bang event about 10^{12} years ago, with formation of hydrogen, the "oldest" element in the universe. Most elements were formed about 5×10^{9} years ago. The continuing decay of parent nuclides since nucleogenesis progressively changes the isotopic composition and hence the atomic weight of the parent and daughter elements.

3. Radionuclides from Reactions of Cosmic Radiation:

A dozen radionuclides are produced in the interaction of cosmic radiations with N, O, and Ar atoms in the upper levels of the atmosphere. The stationary amount is the highest for the long-lived cosmogenic nuclides ^{10}Be, ^{14}C, ^{26}Al, and ^{36}Cl, but the average volume activity is very low because of the enormous dilution factor. The nuclides are formed with an excess of kinetic energy and react like hot atoms, mainly with O2, to form a variety of labeled molecules; some of these are fixed on aerosols. After a variable residence time in the atmosphere, the nuclides reach the surface of the earth in rain and snow. Owing to isotope exchange and biological reactions, ^{3}H ($^{3}T_1$) and ^{14}C are found in many hydrogen and carbon-containing compounds. Activities of the cosmic nuclides are very low and difficult to measure under ordinary conditions.

4. Neutron-Induced Nuclear Reactions:

In minerals containing α-emitting radio elements, neutrons are released in reactions with light elements such as O, N, and F. In turn these neutrons, together with neutrons emitted in the spontaneous fission of 238U, produce reactions similar to those occurring in nuclear reactors, e.g., ^{235}U and ^{238}U.

All radioisotopes are unstable isotopes of elements—undergo nuclear decay and emit some form of radiation. The radiation emitted can be of several types including alpha, beta, gamma radiation, proton and neutron emission along with neutrino and antiparticle emission decay pathways. The emission of electromagnetic energy (such as gamma rays) from the nucleus of an atom. This usually occurs during alpha or beta radioactive decay. These three types of radiation can be distinguished by their difference in penetrating power.

1. α (alpha) radiation: The emission of an alpha particle (which contains 2 protons and 2 neutrons) from an atomic nucleus. When this occurs, the atom's atomic mass will decrease by 4 units and atomic number will decrease by 2.

- These rays or particles have low penetrating power.

- They have positive charge and can be detected by a strong magnetic field.

- They carry two positive charge.

- They have a mass of 4 amu (atomic mass unit)

- Heavy metals have capacity to emit such type of rays.

- All alpha particles are having the same energy.

- The penetrating power of alpha rays is less as compared to other emissions.

- Because of low penetrating power of alpha particles, elements which emit alpha rays do not find use in biological applications because they cannot penetrate tissue. $^{226}Ra_{88} \longrightarrow {}^{4}He_{2} + {}^{222}Rn_{86} \longrightarrow {}^{4}He_{2} + {}^{218}Po_{218}$

$T_{1/2}$ Ra(226)=1600 days and $T_{1/2}$ Rn (222)= 3,82 days

2. β (beta) radiation: The transmutation of a neutron into an electron and a proton. After this happens, the electron is emitted from the nucleus into the electron cloud.

These have 2 types:

a. Electrically positively charged particles which are called 'positrons'

b. Electrically negatively charged particles which are called Negatrons'

- They have greater penetrating power than that of alpha rays.

- Beta particles have negligible mass.

- These particles are usually accompanied by gamma radiation. Beta particles have less ionizing power than alpha particles.

3. γ (gamma) radiation:

- These have been more penetrating than alpha and beta rays.

- They are having the same character as that of very short electromagnetic waves called X-rays.

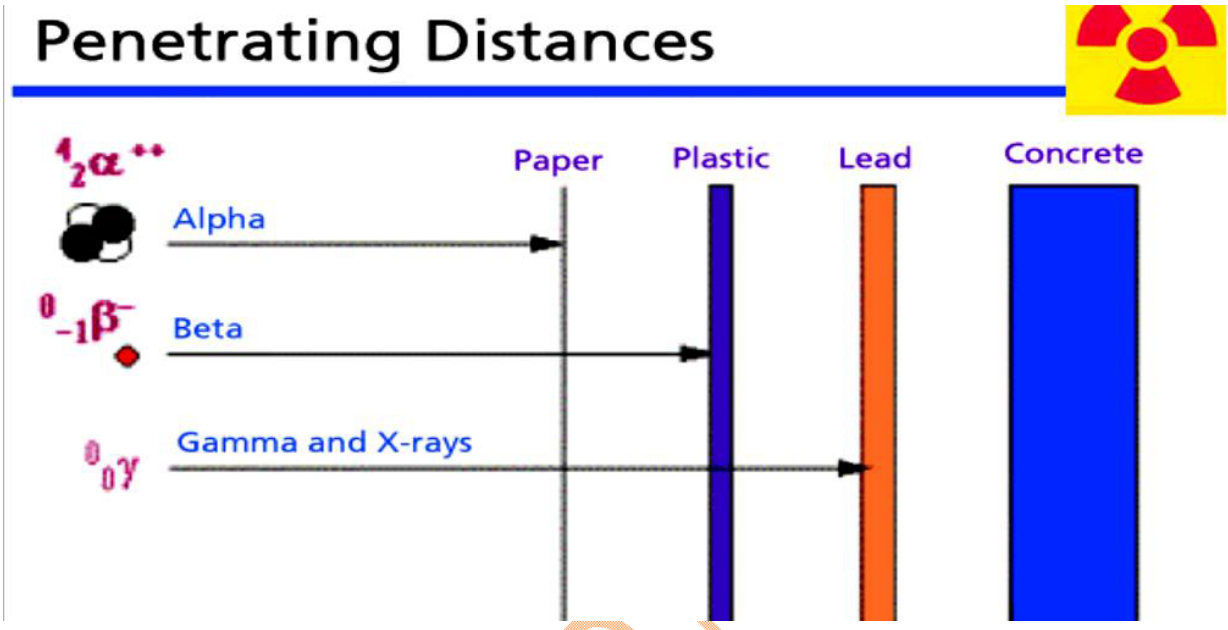
- They have no mass or charge.

- Gamma rays are produced during disintegration of radioactive substances along with beta radiation and during nuclear fission.

- They are uncharged and have poor ionizing power.

Alpha can be stopped quite easily by a few centimetres in air or a piece of paper and is equivalent to a helium nucleus. Beta can be cut off by an aluminium sheet just a few mm thick and are electrons. Gamma is the most penetrating of the three and is a massless chargeless high energy photon. Gamma radiation requires an appreciable amount of heavy metal radiation shielding (usually lead or barium-based) to reduce its intensity.

Activation analysis: By neutron irradiation of objects it is possible to induce radioactivity; this activation of stable isotopes to create radioisotopes is the basis of neutron activation analysis.



Example: Carbon may exist as a number of isotopes and three main isotops are;
$^{11}C_6$ ***Unstable nucleus; prepared by nuclear reaction in a cyclotron.***
$^{12}C_6$ ***Stable nucleus; accounts for 98.89% of natural carbon.***
$^{13}C_6$ Stable nucleus; accounts for 1.11% of natural carbon .

$^{14}C_6$ Unstable nucleus; trace amounts present in living matter.

The atomic mass of an element is the average of the atomic masses and abundances of each of the naturally-occurring isotopes. e.g. The atomic mass of carbon is 12.01.

That is [12.0000x98.89($^{12}C_6$)] + [13.00335x1.11($^{13}C_6$) / 100.

Natural Radioactivity:

Nucleogenesis produces nuclides that can be stable or unstable. Unstable nuclei decay through a range of mechanisms involving the release of particles with high kinetic energy or of γ – radiation. These high-energy products are collectively known as radioactivity.

The four most important radioactive decay mechanisms are:

1. α decay

e.g. 212 208 4

$$^{212}Bi_{83} \longrightarrow {}^{4}He_{2} + {}^{208}Tl_{81}$$

The α particle is simply a helium nucleus with mass 4 and charge 2+. As with all nuclear reactions, both mass and charge are balanced.

2. β decay: β (or β-) is an electron ejected from the nucleus.
One neutron is changed into a proton in this nuclear reaction to balance the charge.

$$^{12}B_{5} \longrightarrow {}^{12}C_{6} + {}^{0}e_{-} ({}^{0}\beta_{-})$$

β (or β-) is an electron ejected from the nucleus.
One neutron is changed into a proton in this nuclear reaction to balance the charge.

3. Positron (β+) emission: $^{12}N_{7} \longrightarrow {}^{12}C_{6} + {}^{0}e_{+} ({}^{0}\beta_{+})$

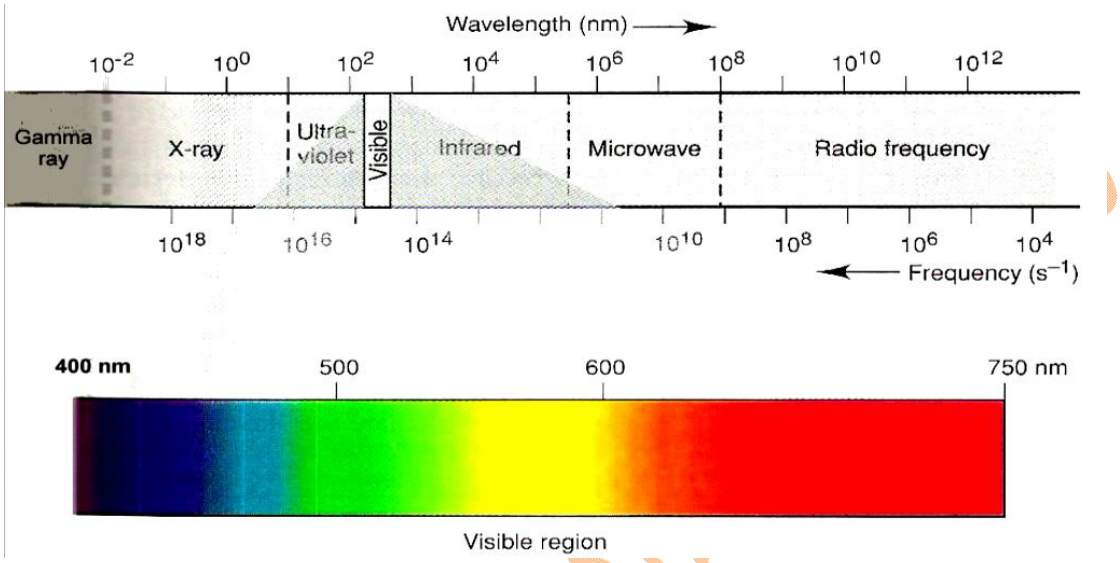
When a positron (β+) is ejected from the nucleus is usually collides with its antiparticle (the electron) in the surrounding environment very soon:

$$e+ + e- \longrightarrow \gamma$$

4. Electron capture:

Electron capture is followed by emission of x-rays as electrons fall into lower energy states to fill the vacancy left by the captured electron. (x-rays are not generally classified as radioactivity, although they can cause radiation damage.)

x-rays have shorter wavelengths than visible or ultraviolet light -between 0.01nm and 10nm. γ –rays have very short wavelengths - less than 0.01nm or 0.1Å.



Nuclear Stability:

What factors determine whether a nucleus is stable or unstable?

If we look at the range of stable nuclides that exist in nature, then there are two main observations

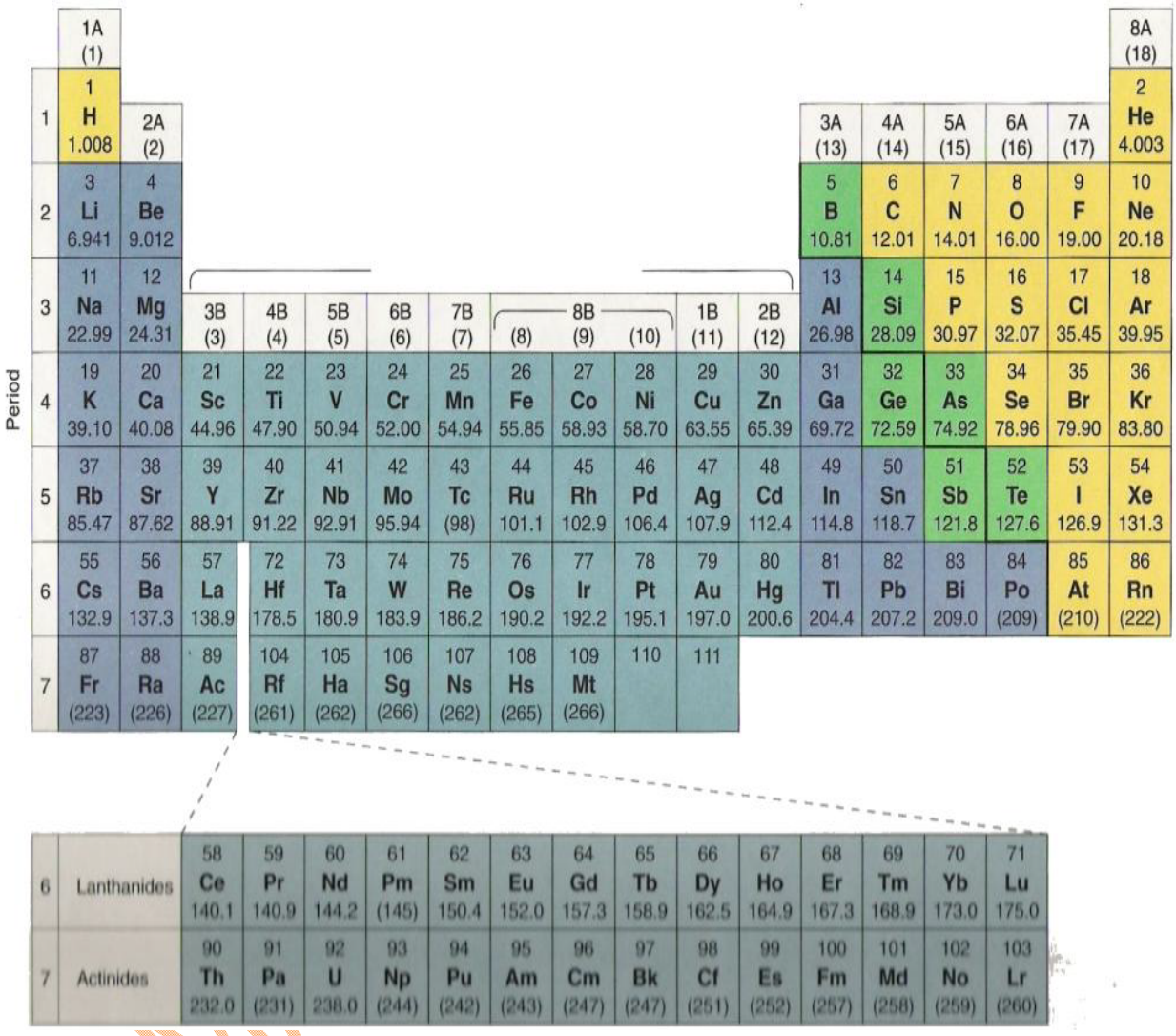
1. The size of the nucleus.

2. The composition of the nucleus (proton: neutron) or N/P ratio.

All known stable nuclides fall inside the zone of stability. This zone has a N:Z ratio near to 1, but "bends" towards more neutrons per proton as the nucleus gets larger.These two observations are enough to give us a "rule" for nuclear stability that goes something like "Unstable isotopes must decay towards the zone of stability, finally falling below $^{209}Bi_{83}$.

The following page shows the periodic table with the band of stable isotopes with radioactive elements that involves lanthanides and actinides like Praseodymium $^{140}Pr_{59}$: [Xe] $4f^3\ 6S^2$ and samarium $^{150}Sm_{62}$: $4f^6\ 6S^2$; Neptunium $^{273}Np_{93}$: [Rn] $4f^4\ 6d^1\ 6S^2$.

There are no stable nuclei heavier than $^{209}Bi_{83}$



Period	1A (1)		3B (3)	4B (4)	5B (5)	6B (6)	7B (7)	8B (8)	8B (9)	8B (10)	1B (11)	2B (12)	3A (13)	4A (14)	5A (15)	6A (16)	7A (17)	8A (18)
1	1 H 1.008	2A (2)																2 He 4.003
2	3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
3	11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
4	19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.90	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.70	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
5	37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (98)	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
6	55 Cs 132.9	56 Ba 137.3	57 La 138.9	72 Hf 178.5	73 Ta 180.9	74 W 183.9	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.6	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po (209)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra (226)	89 Ac (227)	104 Rf (261)	105 Ha (262)	106 Sg (266)	107 Ns (262)	108 Hs (265)	109 Mt (266)	110	111							

6	Lanthanides	58 Ce 140.1	59 Pr 140.9	60 Nd 144.2	61 Pm (145)	62 Sm 150.4	63 Eu 152.0	64 Gd 157.3	65 Tb 158.9	66 Dy 162.5	67 Ho 164.9	68 Er 167.3	69 Tm 168.9	70 Yb 173.0	71 Lu 175.0
7	Actinides	90 Th 232.0	91 Pa (231)	92 U 238.0	93 Np (244)	94 Pu (242)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (260)

Nuclear Stability and Decay Mechanisms:

Consider some of the known isotopes of carbon shown previously. Each nuclide decays towards the zone of stability by changing its N/Z ratio at constant mass number. Each nuclide decays towards the zone of stability by changing its N/Z ratio at constant mass number.

$^{11}C_6 \longrightarrow {}^{11}B_5 + {}^{0}e_{+}({}^{0}\beta_{+})$ to change N/Z from 0.83 to 1.2

$^{55}Fe_{26} + {}^{0}e_{-} ({}^{0}\beta_{-}) \longrightarrow {}^{55}Mn_{25}$ e-capture to change N/Z from 1.11 to 1.2

$^{14}C_{6} \longrightarrow {}^{14}N_{7} + {}^{0}e_{-1} ({}^{0}\beta_{-})$ to change N/Z from 1.00 to 1.33

$^{15}C_{6} \longrightarrow {}^{15}N_{7} + {}^{0}e_{-1} ({}^{0}\beta_{-})$ to change N/Z from 1.5 to 1.14

The "rule" for nuclear stability: "Unstable isotopes must decay towards the zone of stability, finally falling below ^{209}Bi." Heavier nuclides than ^{209}Bi decay by a combination of mechanisms, using a decay to reduce mass (with N/Z =1). The nuclear stability "rule" is empirical, based on the simple experimental observation of which nuclides are stable and which are not. We can apply it like an algorithm to solve some nuclear decay problems, without understanding the reasons for nuclear stability. To understand the reasons, the rule, and the observations, we need to consider the forces between nucleons within the nucleus. The stability of a nucleus involves the competition between two forces;.

1. Coulomb or electrostatic repulsion between protons acts to push these nucleons apart over a long range.
2. The strong nuclear force is a short range attraction between all nucleons.

This is the main function of neutrons in the nucleus. They contribute to the binding of the nucleus without also contributing to the electrostatic de stabilization.

How does this explain our observations?

1. In nuclides with too few neutrons, the electrostatic repulsions overwhelm the strong nuclear attractions.
2. As the nucleus gets larger, the long-range electrostatic repulsion between protons accumulates and eventually overwhelms the strong nuclear attraction, even if N/Z is optimized. This microscopic model does not explain how nuclides with too many neutrons can be unstable. To do so will involve quantum mechanics.

Unstable nuclides are present in nature for two reasons. ???

- Some unstable nuclides have long half-lives, so they simply haven't decayed yet.
- Some unstable nuclides continue to be formed by nuclear reactions.

The decay of an unstable nuclide is characterized by a half-life. This is the time required for half of the nuclei present to undergo a decay event. For each parent

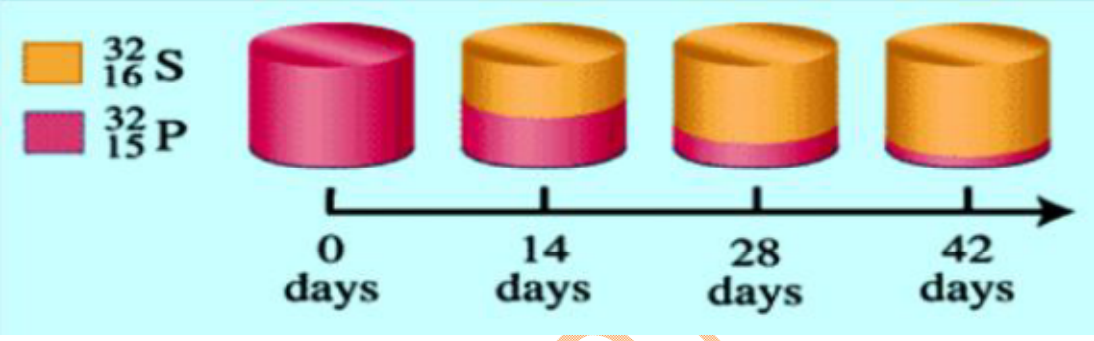
nuclide that decays, one daughter nuclide is produced and a particle or γ is emitted.

e.g 1. $^{212}Bi_{83} \longrightarrow {}^{208}Tl_{81} + {}^{4}He_{2}$ **(alfa particles) emitted particles**

e.g 2. $^{12}B_{5} \longrightarrow {}^{12}C_{6} + {}^{0}e_{-1}({}^{0}\beta_{-})$ **emitted particles**

Rate of Nuclear Decay - Half-Life

e.g. ^{32}P decays into ^{32}S with a half- of 14.7 days.



$^{32}P_{15} \longrightarrow {}^{32}S_{16} + {}^{0}e_{-1}({}^{0}\beta_{-})$

The number of ^{32}P nuclei halves in 14.7 days, and halves again after a further 14.7 days... So, after 14.7 days, half of an initial 10g of ^{32}P will have decayed, leaving 5g. At the same time 5g of ^{32}S will have formed. After a further 14.7 days, only 2.5g of ^{32}P will remain, and 7.5g of ^{32}S will be present…

This also tells us that the rate of decay, the number of nuclei that disintegrate each second, also halves every 14.7 days. The rate of decay halves after every half-life. The disappearance of a radionuclide by radioactive decay is described by the number of nuclei remaining after time t. The activity, A, of a radionuclide is simply the rate of emission, or minus the rate of disappearance of the nuclide. The activity (rate of decomposition) of a sample is proportional to the number of nuclei present. i.e. when the number of nuclei present is halved, the activity is also halved.

Units of Activity :

• Fundamental unit of activity - Disintegrations per second, also known as the becquerel (Bq)

• Curie (Ci) $^{-1}$ Ci equals the number of nuclei disintegrating each second in 1g of $^{226}Ra = 3.70 \times 10^{10}$ counts per second (or Bq).

• Activity and Half-Life are related.

• Low activity (few disintegrations per second) = long half-life.

• High activity = short half-life

• Molar Activity = Activity/mole

• Specific Activity = Activity/gram

Molar Activity, Specific Activity and Half-Life are both independent of the amount of radioactive material present in the sample.

$A = \lambda N = 0.693\ N / t_{1/2}$

• Molar Activity = Activity / mole $AM = \lambda NA = 0.693\ NA / t_{1/2}$

• Specific Activity = Activity / gram $AS = \lambda NA = 0.693/t1/2(NA/M)$

M = atomic mass

Molar Activity, Specific Activity and Half-Life are both independent of the amount of radioactive material present in the sample.

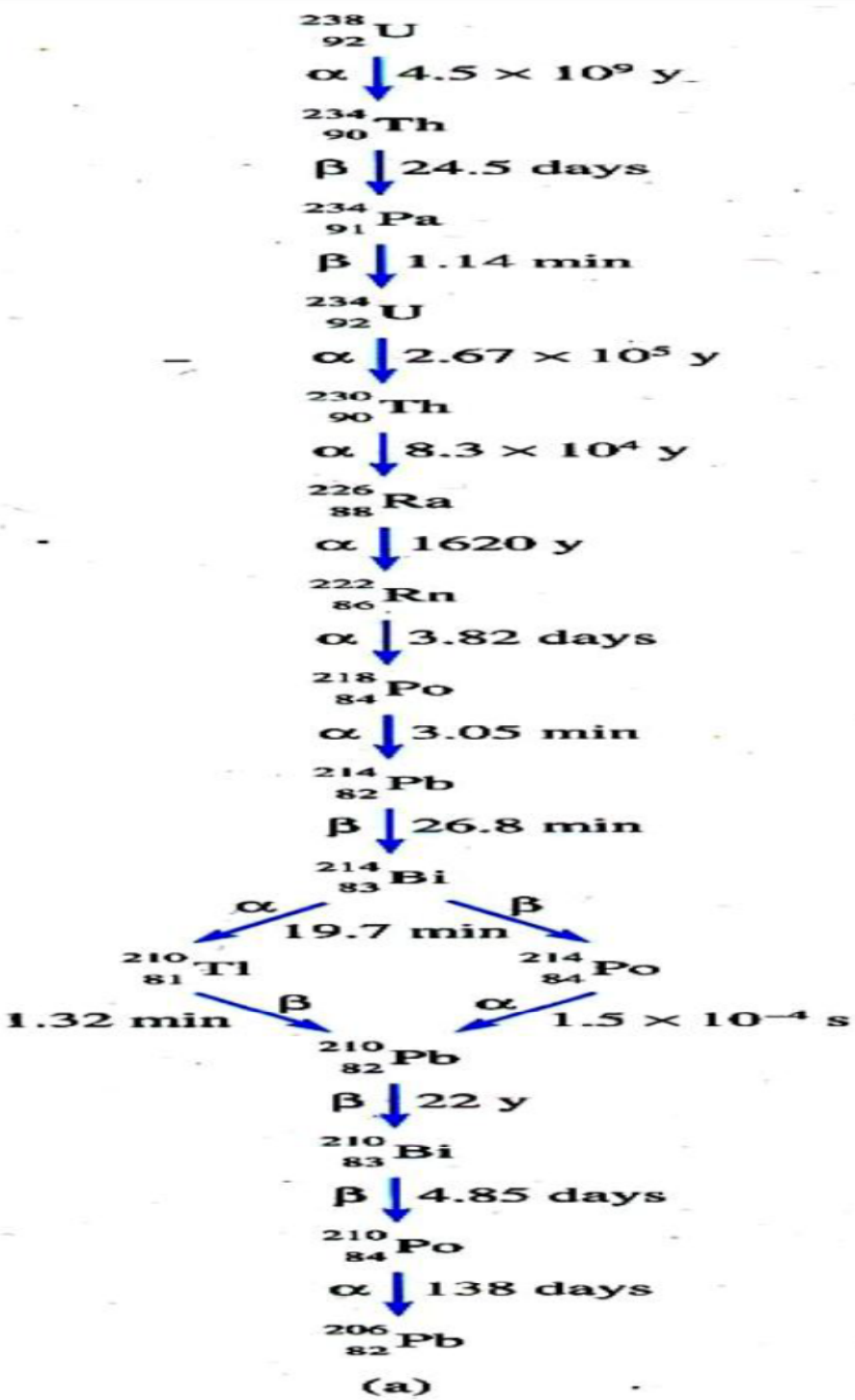
Example: What is the molar activity of ^{13}N, which has a half life of 9.96 minutes?

Answer. $AM = \lambda NA = 0.693\ NA / t1/2$; 9.96 minutes = 598s

$AS = 0.693 \times (6.022 \times 10^{23}) / 598 = 6.98 \times 10^{20}$ disintegrations $mol^{-1}\ s^{-1}$ (or Bq mol-1)

Decay Series:

In a decay series, each step in the mechanism has its own half-life. Notice that the half-life of ^{238}U is 4.5x109y, so that many of the atoms present when the earth was formed still have not decayed. However the daughter nuclides decay much more quickly. Notice also that half lives can be as long as billions of years or as short as a ms or less.


$^{238}_{92}U$
α | 4.5 × 10⁹ y
$^{234}_{90}Th$
β | 24.5 days
$^{234}_{91}Pa$
β | 1.14 min
$^{234}_{92}U$
α | 2.67 × 10⁵ y
$^{230}_{90}Th$
α | 8.3 × 10⁴ y
$^{226}_{88}Ra$
α | 1620 y
$^{222}_{86}Rn$
α | 3.82 days
$^{218}_{84}Po$
α | 3.05 min
$^{214}_{82}Pb$
β | 26.8 min
$^{214}_{83}Bi$
α
19.7 min
β
$^{210}_{81}Tl$
$^{214}_{84}Po$
1.32 min
β
α
1.5 × 10⁻⁴ s
$^{210}_{82}Pb$
β | 22 y
$^{210}_{83}Bi$
β | 4.85 days
$^{210}_{84}Po$
α | 138 days
$^{206}_{82}Pb$

(a)

Radiocarbon Dating:

99.9% of the naturally abundant ^{14}C is produced in the upper atmosphere by neutrons reacting with ^{14}N, which then enters the carbon cycle. The production rate is 2.5 atom cm^{-2} s^{-1} with a global inventory of 3 x 10^{30} 14C atoms (90% oceans, 8% biosphere and soils, 2% atmosphere). Typical ^{14}C concentration in sea waters is 1.2 x 109 ^{14}C atoms/L (2 x 10^{-15} M).

$$^{14}N_7 + {}^{1}n_0 \longrightarrow {}^{14}C_6 + {}^{1}P_1$$

^{14}C is an example of an isotope that is continuously produced in our environment. ^{14}C can be produced underground, directly or indirectly, by the decay of uranium and thorium series. An estimate of this 14C can be useful in the study of hydrological environments where uranium and thorium contents are high.

All organic living matter contains a fixed fraction of ^{14}C amongst all its carbon. This comes mostly (from atmospherically generated) material taken up by bio- chemical paths. After death, ^{14}C no longer accumulates, and decays into with a half-life of (5730) y. Thus comparing the concentration of ^{14}C in dead and comparable living matter can tell us how long since the sample died.

How is the amount of ^{14}C determined? 14C undergoes β decay?

$$^{14}C_6 \longrightarrow {}^{14}N_7 + {}^{0}e_{-1}$$

Radiocarbon dating can be achieved either

- by measuring the concentration of ^{14}C present in a sample, or
- by measuring the activity due to b emission. (Recall that activity is proportional to the number of decaying nuclei:)

$$A = \lambda N = 0.693N/t_{1|2}$$

Scintillation counter:

Scintillation is the emission of light when exposed to ionizing radiation. Scintillation counters simply measure the intensity of light emitted as a result of exposure to a radiation source. By calibration against a standard, this can read activity directly.

Accelerator mass spectrometry (AMS): AMS is a high precision mass spectrometry technique that can measure small amounts of sample and resolve

isotopic composition. In ^{14}C dating, AMS is used to measure the ratio of $^{14}C/^{13}C$ and $^{14}C/^{12}C$.

As ^{13}C and ^{12}C are stable, these ratios can be used directly to obtain radiocarbon age. As carbon from different sources can have slightly different isotopic ratios due to various chemical processes, the ratio of $^{13}C/^{12}C$ is measured directly in AMS as an additional calibration correction.

Biological Effects of Radiation:

How do various forms of radiation interact with (biological) matter?. The basic characteristic of radiation produced by radioactivity is that it is high energy, and causes the ionization of matter by ejecting an electron from an atom. (It's generally called ionizing radiation.)
(When radiation is stopped my matter, it has interacted with it and therefore caused ionization. Highly penetrating radiation passes through matter without ionizing it.)
Ionization produces free radicals. These are highly reactive chemical species.
E.g. Gamma irradiation of water ejects an electron creating a radical ion

$$H_2O + \text{gamma} \longrightarrow \mathbf{H_2O^+ + e^-}$$

Both products lead to the production of more free radicals

$$H_2O + \mathbf{H_2O^+} \longrightarrow \mathbf{H_3O^+ + OH^-}$$

$$\mathbf{e^- + H_2O} \longrightarrow \mathbf{H^\cdot + OH^\cdot}$$

Free radicals attack biomolecules such as DNA strands or membrane lipids. This can (infrequently) lead to genetic damage, cancers, disruption of cell membranes, or malfunctions in enzymes that regulate biological processes. Biological exposure arises through a variety of mechanisms.

E.g. Direct exposure to a radioactive source (external) Solid or liquid: Localized around shielding.

E.g. Contamination (external and internal)

External: Picking up radioactive material on hands, shoes, etc...

Internal: Ingestion or inhalation.

The risk of damage from a particles through internal contamination is much higher than external, where they are quite well shielded by your skin.

Nuclides with longer half-lives disintegrate at lower frequency. That is, longer half lives equals lower (molar) activity, so lower potential for ionization and radiation damage. From this point of view ^{238}U, with a half-life of 4.5 billion years, or ^{230}Th ($t_{1/2}$= 83,000 y) is less damaging than ^{3}H ($t_{1/2}$= 12 y) or ^{234}Th ($t_{1/2}$= 24.5 days).

$$A = \lambda N = 0.693N/t_{1l2}$$

Units of Radiation Dosage:

(Human) Radiation dosage is measured in rems (or millirems) or in Sieverts (Sv). Dosage attempts to include all the factors that can affect a living organism -activity, energy, penetration, and the mass of living matter irradiated. The total expected dosage for an average person is about 360 mrem/year.

What are the short-term effects of radiation dosage?

25,000 mrem in 24h No detectable effects
50,000 mrem in 24h Slight temporary blood change
100,000 mrem in 24h Nausea & fatigue
200,000 mrem in 24h First death (no medical intervention)
500,000 mrem in 24h LD50 (50% of humans exposed die.).

Common Sources of Radioactivity:

We are exposed to several common natural sources of radioactivity. These account for about 300mrem/year. The most common is radon, which is part of the decay series of 238U and other heavy elements, and decays into polonium with a half-life of 3.82 days.

$$^{222}Rn_{86} \longrightarrow {}^{218}Po_{84} + {}^{4}He_{2}\ (_{2}\alpha^{4})$$

α decay of radon gas causes damage to lungs and is thought to be responsible for up to 10% of lung cancers. Other ambient isotopes include as dissolved potassium ions, and in CO_2 and organic compounds. Other ambient isotopes include:

$_{19}K^{40} \longrightarrow {}_{18}Ar^{40} + {}_{+1}e^{0}$ **as dissolved potassium ions, and**

$_{6}C^{14} \longrightarrow {}_{7}N^{14} + {}_{-1}e^{0}$ ***in CO_2 and organic compounds.***

Medical Imaging:

Basic principles of medical imaging includes;

• Use a radioisotope to specifically target a chemical agent, organ or process in the body with high selectivity.

• Isotope should emit low-energy, highly-penetrating radiation to minimise effective dosage equivalent to patient. In practice this usually means g.
• Image distribution of radioisotope (by its activity) using scintillation counting
– gamma camera (planar image like an x-ray) or
– computer-assisted tomography (CAT or CT scan - cross section or three-dimensional reconstruction)
• Images may be a simple gray scale density or pseudo-colour signal. Pseudo colour is especially common in computer-reconstructed imaging.
Technetium-99m (^{99m}Tc) is used in about 85% of radio nuclear chemistry. It is formed by the decay of ^{99}Mo by:

$_{43}Tc^{99m} \longrightarrow {}_{43}Tc^{99} + \gamma$

^{99m}Tc is a wholly synthetic element and is unknown in nature. It has no stable isotopes. Technetium-99m a metastable isomer that decays into ^{99}Tc by γ emission with a half-life of 6h.

Then decays into Ru by β emission, but with a half-life of 2.1 x 10^5 y.

$^{99}Tc_{43} \longrightarrow {}^{99}Ru_{44} + {}^{0}e_{-1}$ (Negatron).

Chemical Generation of ^{99m}Tc from ^{99}Mo :

• ^{99}Mo has a half-life of 67h. It can be used for ~1 week as a continuous source of 99mTc, which it replenishes after extraction
• Extraction is based on the differential solubility of molybdate (MoO42-, insoluble) and pertechnetate ions (TcO4-, soluble) in NaCl solution.
$^{99}MoO_4^{2-}$ is supplied in a cartridge, precipitated or adsorbed onto the

surface of a support like alumina (Al_2O_3). This is flushed with saline solution to extract the daughter isotope 99mTc for use.

• Pertechnetate ion(TcO_4^{2-}) soluble in water, may be used directly for imaging, e.g. thyroid or blood circulation, or it may be chemically transformed to target other sites.

Several other generators are also used, exploiting chemical changes accompanying radioactive decay to form and separate short half-life nuclides for imaging.

eg.

$$_{38}Sr^{82} \longrightarrow {}_{37}Rb^{82} + {}_{-1}e^{0} \qquad t_{1/2}(^{82}Rb) = 76\ s$$

How is ^{99m}Tc used?

^{99m}Tc is incorporated into a wide variety of compounds that are used to specifically target sites in the body.

E.g.1. Technetium pyrophosphate is used to target bones and identify bone cancer, as in gamma camera image and also technetium penetrate is used to monitor kidney function. Nuclear imaging is useful because it allows us to radiolabel molecules that specifically target organs, molecules or chemical processes for diagnosis or biochemical research.

Radiopharmaceuticals

What are radiopharmaceuticals? Units of radioactivity.

1. Curie (c) : Defined as quantity of any radioactive substance which undergoes the same number of disintegrations in unit time as of 1 g of radium and is equal to 3.7 x10^{10} disintegrations per second.

2. Roentgen: it is the unit of exposure 1R= 2.58 x 10^{-4} coulomb kg-1

3. RAD: it is the unit of absorbed dose. Pharmaceutical dosage forms are described in RAD units.

4. REM: I t is unit of dose equivalent.

5. Exposure rate constant

6. RBE (Relative biological effectiveness): shows effect of radiation, alpha, beta and gamma on the biological system.

Production of Radioisotopes:

They are produced as:

1) Reactor irradiation: Reactor is having an arrangement of fissionable material in a moderator, which slows down the fast neutrons to thermal energies. The fissionable material like uranium is taken in the form of rods which are arranged in a lattice pattern and hence the neutron flux is maximum in the centre where there is most uranium. A heavy water moderated reactor using enriched uranium is having a maximum flux of 10^{14} neutrons cm^{-2} s^{-1}.

2) Cyclotron irradiation: While the reactors are able to produce a flux of neutrons and gamma rays, accelerating mechanisms can use many other types of bombarding particles which have been charged particles. They can be accelerated to high velocities so as to overcome the repulsive forces of the nucleus. The beam of energetic particles has been small and targets for irradiation have to be put in this beam. The number of samples that can be irradiated at a time has been limited and the yields has been low. But on the other hand many isotopes which otherwise cannot be produced in a reactor could be produced in a cyclotron.

Examples of some uses:

Sodium iodide I-^{131}

- Used as a diagnostic aid for studying the functioning of the thyroid gland.
- Used in scanning the thyroid for determining the size, position and possible tumour location.
- Used in the treatment of severe cardiac disease (Sodium iodide I-131), which reduces work load on heart.
- Radioactive iodine in thyroid carcinoma (cancer): The isotope is used most frequently after the surgical removal of cancer to treat any residual tumour tissues.

Iron 59:Fe

- Iron 59 is a beta and gamma emitting isotope.

- Used in diagnosis to study the iron metabolism and to study the red blood cell formation.
- The preparation is administered orally for studying the absorption of iron from GIT.

- Administered I.V to study incorporation of iron in formation of red blood cells.

- Used to study the formation and destruction of spleen, liver etc. from outside the body.

Applications of Radioisotopes :

They find use in medicine in 4 different ways:
1. Radioisotopes in Therapy (Emitted radiations used to destroy cells in condition like cancer).

2. Radioisotopes in Diagnosis (Radioactive tracers).

3. Research (Biological and medicinal studies by use of radioactive isotopes as tracers).

4. Sterilization (For sterilization of pharmaceuticals and surgical instruments)

Diagnostic applications: Radiopharmaceuticals are developed based on the ADME (absorption, distribution, metabolism, excretion) properties of the body. By administering a radiopharmaceutical to a patient, images of the targeted site can be produced by a gamma camera. The images can then be analyzed by the nuclear medicine doctor to detect any medical problems. Radiopharmaceuticals are most widely used to detect various forms of cancer. Depending on the site for diagnosis there is a specified route of administration.

Therapeutic use of Radiopharmaceuticals:

Radioactivity can be used in medicine and pharmacy in different areas, the first being radiology, in which an external source of radioactivity passes through a patient and radiation is absorbed by more dense tissues and not by less dense tissues and an image is ultimately formed. The second is radiation therapy, which treats for tumors using an external source of radiation to try and ablate a tumor. This requires lots of radiation in very high doses. Nuclear medicine uses an internal source of radiation to be detected externally, unlike the two previously

mentioned. A patient is injected with a radiopharmaceutical, which has a radioactive component that decays and a pharmaceutical component which takes it a desired organ. Radiopharmaceuticals can be used to destroy malfunctioning cells. This method of therapy is called radiotherapy. It can be used for both benign and malignant cancers. In order to destroy the diseased tissue, a radionuclide has to emit beta, alpha, or low energy conversion electron emitters. Beta radiation is effective for large tumors and alpha radiation is effective for smaller tumors.

Therapeutics:

- The therapeutically used radioisotopes have been found to depend mainly on their ability to ionize atoms.
- The energy measurement involved in radiation and resulting in ionization may be expressed in millions of electron volts called MeV.
- The strength of alpha, beta and gamma rays in expressed in MeV.
- All radiations bring about ionization of atoms in their paths.
- The radiation of short wavelength (gamma rays) is having high penetrating power than long wavelength (beta rays).
- The greater the MeV of the rays, the more destructive it becomes to the surrounding tissues.(Radiopharmaceutical can destroy malfunction cells)
- This method of therapy is called radiotherapy. It can be used for both benign and malignant cancers.

Examples:

- Gold (^{198}Au) is used in treatment of abdominal and pleural effusions associated with malignant tumors. It is given in the form of colloidal gold suspension.
- Gold (^{198}Au) also used in treatment of carcinoma of uterus and urinary bladder.
- Cobalt labelled cyanocobalamine (Vitamin B12) is used in diagnosis of pernicious anaemia.
- Sodium iodide preparation finds use in treatment of thyroid disorders.
- Calcium is used to study bone structure and in carcinoma of bone.
- Strontium - Sr^{90} is used in diagnosis of superficial carcinomas.