NUCLEAR CHEMISTRY-UNIT VI

Bequerel-Discovered radioactivity in1896

In 1898 Pierre and Madame Curie isolated radium and polonium from minerals containing uranium and thorium.

More experiments showed that the nuclei of atoms can undergo nuclear reactions.

Controversy about radiation:

a) Radiation can diagnose and treat cancer, but radiation can also cause.
b) The controlled use of nuclear reactions in nuclear power plants could provide electrical energy; but the radioactive wastes produced must be shipped and stored for thousands of years.
c) Nuclear weapons.

Radioactivity: (radioactive decay) It is the spontaneous emission of particles, energy, or both from the nucleus of an atom.

Decay series:

Characteristics of α βand γ- radioactive emission:

	Alpha	Beta	gamma
symbol	${}^{4}_{2}\alpha$, ${}^{4}_{2}He$	${}^{0}_{-1}\beta$, ${}^{0}_{-1}e$	0
mass	4.0026amu	.000549 amu	0
charge	2+	- 1	0
Penetrating power	low	100 times that of the α-particle. It can pass through a paper	Highest penetrating power. Easily penetrating the skin and severely damage internal organs.
Shielding required	Paper, skin, clothing (0.1 mm Al)	Heavy cloth, wood, (0.10 cm Al)	Lead, concrete (1 cm Al)

The symbols for elementary particles:

Proton	neutron	electron	positron
${}^{1}_{1}p$, ${}^{1}_{1}H$	${}^{1}_{0}n$	${}^{0}_{-1}e$, ${}^{0}_{-1}\beta$	${}^{0}_{+1}e$, ${}^{0}_{+1}\beta$

Could a negative particle be emitted from a nucleus?

Since β-particles or electrons are not found in the nucleus, they are believed to form by the decomposition of a neutron in the nucleus into a proton and an electron.

$${}^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e$$

If a β-particle is emitted from a nucleus, the number of protons in the nucleus is _________

By one and the mass number (number of protons and neutrons) is ___________

Nuclear Reactions: One element can be converted into another.

a) Natural radioactivity:

The nuclear symbol: ${}^{A}_{Z}X$ (representation of an isotope or a nuclide)

What is the rule in balancing a nuclear equation?

The rule is the sum of the atomic numbers and the sum of the mass numbers must be the same on both sides of the equation.

a) Alpha-emission: The emission of α-particle:

$${}^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He}$$

b) Beta-emission

$${}^{90}_{38}\text{Sr} \rightarrow {}^{90}_{39}\text{Th} + {}^{0}_{-1}\text{e}$$

c) Gamma-emission

$${}^{60}_{27}\text{Co} \rightarrow {}^{60}_{28}\text{Ni} + {}^{0}_{-1}\text{e} + {}^{0}_{0}\gamma$$

We can use a balanced nuclear equation to find out what element forms in a nuclear reaction:

Example: Identify the nuclide produced and write a balanced nuclear equation for:

a) The emission of α-particle:

${}^{239}_{94}\text{Pu} \rightarrow$ ______ $+ {}^{4}_{2}\text{He}$

b) The emission of β-particle:

${}^{14}_{6}\text{C} \rightarrow$ ______ $+ {}^{0}_{-1}\text{e}$

Artificial Radioactivity: (transmutation) -Induced nuclear radiation.:

In 1932 Chadwick discovered the neutron by bombarding Be-14 with α-particles to give a neutron and carbon-12.

Artificial radioactivity is done by bombarding nuclides of one element with particles such as neutrons, protons, or alpha-particles.

a) ${}^{10}_{5}\text{B} + {}^{4}_{2}\text{He} \rightarrow$ ______ $+ {}^{1}_{0}\text{n}$ Short notation: ${}^{10}_{5}\text{B}({}^{4}_{2}\alpha, {}^{1}_{0}\text{n}){}^{13}_{7}\text{B}$

b) ${}^{9}_{4}\text{Be} + {}^{4}_{2}\text{He} \rightarrow$ ______ $+ {}^{1}_{0}\text{n}$ Short notation: ______________

Platinum-198 can be converted into gold-199 by bombardment with neutrons:

Some of the particles involved in the production of the transuranium elements: All are man made.

particle	Mass(amu)	charge	Symbol
Proton	1	+1	${}^{1}_{1}\mathrm{H}$
Deuterium	2	+1	${}^{2}_{1}\mathrm{H}$
Tritium	3	+1	${}^{3}_{1}\mathrm{H}$
Neutron	1	0	${}^{1}_{0}\mathrm{n}$,
Positron	1/1850	+1	${}^{0}_{+1}\mathrm{e}$, ${}^{0}_{+1}\beta$
neutrino	Less than $2\text{x}10^{-5}$	0	${}^{0}_{0}\nu$

Nuclear stability:

Let us consider the empirical rules for predicting nuclear stability:

1) Nuclei of atomic number higher than 83 are radioactive.
2) Nuclei with even number of nucleons (that is, protons and neutrons) are generally more stable than those with odd number of nucleon.

Protons	even	even	odd	odd
Neutrons	even	odd	even	odd
Number of stable isotopes	157	52	50	5

This leads to the nuclear shell model. It is believed that nucleons occupy shells. The nucleus is most stable when the nucleons are paired up as the electrons in orbitals.

3)Magic numbers: Nuclei that contain certain specific numbers of protons and neutrons possess a degree of extra stability. The so-called magic numbers are:

2, 8, 20,28,50,82,126

That applies separately to neutrons and protons. When nuclei contain a magic number of both protons and neutrons, they are said to be "doubly-magic" and extremely stable.

Examples are: ${}^{4}_{2}\mathrm{He}$ ${}^{16}_{8}\mathrm{O}$ ${}^{40}_{20}\mathrm{Ca}$ ${}^{208}_{82}\mathrm{Pb}$

The occurrence of these magic numbers suggests a shell structure for the nucleus some how similar to the shell structure exhibited by electrons. Recall, that very stable (unreactive) electron configuration occurs when an atom contains magic number of electrons:2, 8, 18, 36, or 54; corresponding to the noble gases. In the nucleus, it seems that nuclear shells of either protons or neutrons become completed when the nuclear magic numbers are reached and that a particularly stable nucleus occurs whenever there is a completed shell of either neutrons or protons.

4) For elements of low atomic number (atomic number less than 20), the nucleus is stable when N/P ratio is almost one to one. As the atomic number increases, the N/P ratio of the stable nuclei becomes greater than 1. This deviation arises in a heavy element because a larger number of neutrons is needed to stabilize the nucleus by counteracting the strong repulsion among the protons.

Does the ratio of neutrons to protons in the nucleus have anything to do with radioactivity?

Belt of stability:

Most of the radioactive nuclei lie outside the belt of stability.

A) Above the stability belt: Nuclei have higher N/P ratio than those in the belt (for the same number of protons). To lower the N/P ratio , hence move down toward the belt of stability, the nuclei must undergo the following:

Beta emission:

B) Below the stability belt : The nuclei have lower N/P ratio than those in the belt(for the same number of protons). To increase the ratio and hence move up the stability belt, these nuclei must:

i) emit a positron:

ii) Undergo electron capture:

B) <u>Beyond the belt of stability</u>: These are elements having a higher atomic number than 82 . Those lie beyond the end of the band of stability. The nuclei must lose both protons and neutrons.

<u>Alpha emission</u>:

<u>Half-life and Rate of Radioactive Decay:</u>

Half-life is the time it takes for one-half the nuclei in a given amount of radionuclide to decay into another nuclide. That is after one-half ime, one-half of the original sample of a radioactive element will have decayed to form a new nuclide.

<u>Example:</u>

${}^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}e$ $\qquad$ $t_{1/2} = 5730$ years

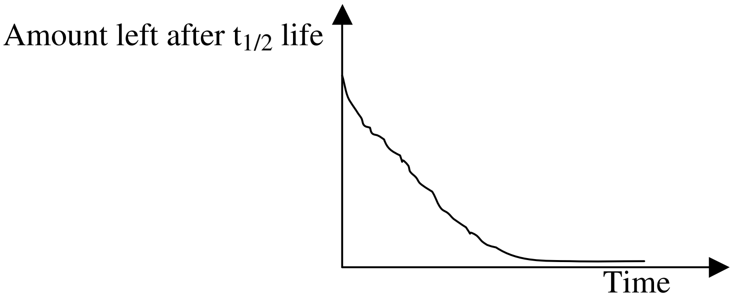

Figure: Number of radioactive atoms versus time.

<u>Some unstable nuclides give α, β, or γ radiation faster than others</u>:

<u>Half-lives of selected radionuclides:</u>

Name	Half-life	Radiation emitted
Polonium-218	3.0 min	α, β
Potassium-42	12.4 hrs	β, γ
Iodine-31	8 days	β, γ
Strontium-90	28 days	β
Uranium-235	710 million yrs	α, γ

Rate of Radioactive Decay:

Nuclear decay involves a first-order rate equation:

$$-\frac{dN}{dt} = k\ N$$

After integration and rearranging:

$$\boxed{\begin{array}{l} \text{Log}\ \dfrac{N^\circ}{N} = \dfrac{k\ \ t}{2.303} \\ \quad t_{1/2} = \dfrac{0.693}{k} \end{array}}$$

Example: Strontium-90 is a β-emitter with half-life of 28.8yrs. How many years will it take for 99.0 percent of a given sample of strontium-90 released in an atmospheric test of an atomic bomb to disintegrate?

Uses of Radionuclide

1) Finding the age of ancient objects:

The estimated age of the earth and the moon has been found by measuring the amount of stable lead-206 accumulated in rocks.

$$^{238}\text{U} \rightarrow {}^{206}\text{Pb} \qquad t_{½} = 4.51\ \text{x}10^{9}\ \text{yrs}$$

After 4.5 billion years, a sample of rock that originally contained 1.0 g of uranium-238 will contain 0.5 g of uranium-238 and 0.43 g of lead-206.

Assuming that no lead-206 was present originally during the formation of the rocks and that the minerals did not undergo chemical changes that would allow lead-206 to be separated from the parent uranium-238, it is possible to estimate the age of the earth. The age of the earth was found to be 4.5 billion years.

2) Radiocarbon dating:

Carbon-14 can be used to estimate the age of plants, wood, teeth, fossils and other carbon containing substances from plants and animals. The technique is based on knowledge that carbon-14 is continuously formed in the upper atmosphere when neutrons react with nitrogen-14.

$$^{1}_{0}\text{n} + {}^{14}_{7}\text{N} \rightarrow {}^{14}_{6}\text{C} + {}^{1}_{1}\text{H}$$

(carbon-14 is continuosly formed in the upper atmosphere when neutrons react with nitrogen-14. Carbon-14 forms CO_2

which eventually is used by plants to make plant tissues. Since animals eat plants containing radioactive carbon-14 then all animals and plants contain some radioactive carbon-14 . In all living tissues, there is sufficient carbon-14 to produce about 15 rays per minute per gram of carbon-14 in the tissue. When an organism dies, the remaining carbon-14 begins to decrease. Since $t_{1/2}$ for carbon-14= 5760 yrs, it takes that long for the rate of decay to go from 15 rays/min per gram of carbon to 7.5 rays. By determining the number of rays an ancient object emits, an archaeologist is able to estimate the age of the object.)

Example: Using the radiocarbon dating procedure, a sample of wooden object was found to give 8.00 ^{14}C counts/min per gram of carbon. Calculate the age of the object. The activity of ^{14}C in living plants and animals is found to be 15.3 disintegrations per minute per gram, and $t_{1/2}$ $(^{14}C) = 5.77 \times 10^3$ years.

3) Medical uses

a) Treatment of cancer.
b) Diagnosis

Binding Energy

Einstein's equation: (The equivalence of mass and energy)

$\Delta E = \Delta mc^2$ Where, ΔE=binding energy, Δm=mass defect, c=speed of light

Example: Calculate the binding energy of krypton-84 expressed as ergs/atom. The actual mass of one atom of krypton-84 is 83.9115 amu. The mass of 1 proton is 1.00728 amu, 1 electron is 0.000548 amu and 1 neutron is 1.00867 amu.

We need to calculate the mass defect, Δm. In forming the nucleus from protons and neutrons, that much mass is converted to energy. The equivalent amount of energy would be required to dissociate the nucleus back into protons and neutrons.

Example: The atomic mass of iodine-127 is 126.9004 amu. Calculate the nuclear binding energy of this nucleus and the corresponding nuclear binding energy per nucleon expressed as joules.

Nuclear Fission:

It is believed that the result of neutron bombardment is the formation of an isotope of the next higher element by a process of γ-decay.

In 1939, it has been discovered that uranium-235 is split into smaller fragments by bombarding uranium-235 with slow neutrons.

$$^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{140}_{56}Ba + {}^{93}_{36}Kr + 3\ {}^{1}_{0}n + \text{Energy}$$

A nuclear chain reaction initiated by one neutron fissioning a single uranium-235. The splitting of an atomic nucleus into two or more fragments is called nuclear fission. There is a small loss of mass when a large nucleus is split into smaller fragments. This is transformed into energy. Most of the neutrons released by fissioning uranium-235 nuclei in this case will collide with nuclei of uranium-238, either loosing energy without bringing about any nuclear reaction, or else being absorbed ultimately forming plutonium (which is fissionable) used in the breeder reactor.

The energy released from 1 mole of uranium-235 (235 g, 1 lb) equals that from burning 570,000 liters of gasoline. The source of this energy is the conversion of a tiny amount of mass into energy. The fission of 1 gram uranium will produce energy equal to that produced from burning 2.5 million grams of coal.

The abundance of uranium-235 is low; uranium-238 is 99.28% and uranium-235 is 0.71 %.

A Simplified Nuclear Reactor:

A nuclear reactor contains:

a) a fissionable isotope such as uranium-235.
b) a moderator as graphite to slow down fast neutrons.
c) control rods as cadmium to absorb excessive neutrons.

The fission of uranium -235 can be accomplished in a controlled fashion for the purpose of providing energy. The energy released by the fission process is used to heat water to produce steam. The steam is used to turn the blades of a giant turbine for producing electric energy.

Nuclear Fusion:

It is a nuclear reaction in which extremely high temperature is used to unit or fuse two nuclei with low mass numbers such as hydrogen to form a nucleus with a larger mass number as helium. In the process an enormous amount of energy is produced as a small amount of mass is changed into energy.

$$^{2}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}He + ^{1}_{0}n + \text{Energy}$$

Because of the high temperature needed, fusion is more difficult to initiate than fission. Controlled nuclear fusion as a source of electric power has yet to be accomplished. Because light nuclei are so plentiful, the fusion reaction is a potential source of unlimited energy.