Chapter 20

NUCLEAR CHEMISTRY

(Part I)

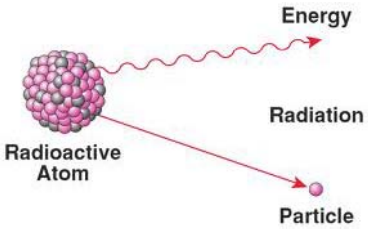
Nuclear Chemistry

- ***Nuclear chemistry*** is a subfield of chemistry dealing with radioactivity, nuclear processes and nuclear properties.

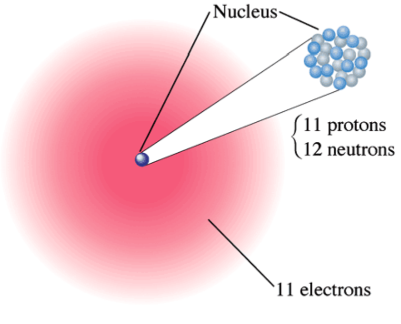
Every year on the 6th of August, Hiroshima holds the *atomic bomb memorial*. The attack by the USA in 1945 with an atomic bomb was one reason for Japan to surrender. This had ended World War II

Radioactivity

- ***Radioactivity*** is a spontaneous emission of *particles* and/or *electromagnetic radiation* by chemical elements (most elements with an atomic number greater than 83). These elements are called *radioactive*.
- ***Radioactive decay*** is the process when unstable nuclei emit *particles* or *electromagnetic radiation*.



Atomic Number and Mass Number



This is also known as a ***nuclide***.

Mass number

$$^{23}_{11}\text{Na}$$

Atomic number

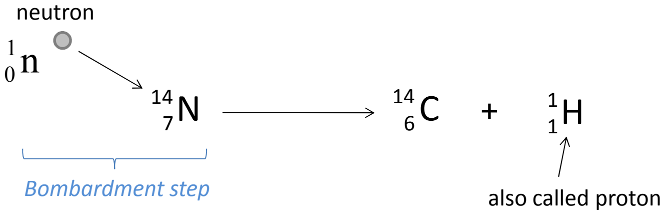
Element symbol

Mass number = # of protons + # of neutrons

Atomic number = # of protons

Nuclear Transmutation

- ***Nuclear transmutation*** (also known as *nuclear transformation*) is the process where a specific nucleus is bombarded (*is hit*) by a neutron, an electron or another nucleus.



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

- *Are there reactions associated with nuclear processes?*

  Yes, there are. But they are very different from ordinary chemical reactions.

Chemical Reactions vs. Nuclear Reactions

TABLE 20.1 Comparison of Chemical Reactions and Nuclear Reactions

Chemical Reactions	Nuclear Reactions
1. Atoms are rearranged by the breaking and forming of chemical bonds.	1. Elements are converted to other elements (or isotopes).
2. Only electrons in atomic or molecular orbitals are involved in the reaction.	2. Protons, neutrons, electrons, and other subatomic particles such as α particles may be involved.
3. Reactions are accompanied by the absorption or release of relatively small amounts of energy.	3. Reactions are accompanied by the absorption or release of tremendous amounts of energy.
4. Rates of reaction are influenced by temperature, pressure, concentration, and catalysts.	4. Rates of reaction normally are not affected by temperature, pressure, or catalysts.

$H_2\,(g) + O_2\,(g) \rightarrow H_2O\,(l)$

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

Subatomic Particles

- The symbols of some subatomic particles are as follows:

${}^{1}_{1}\mathrm{H}$ or ${}^{1}_{1}\mathrm{p}$	${}^{1}_{0}\mathrm{n}$	${}^{0}_{-1}e$ or ${}^{0}_{-1}\beta$	${}^{0}_{+1}e$ or ${}^{0}_{+1}\beta$	${}^{4}_{2}\alpha$ or ${}^{4}_{2}\mathrm{He}$
proton	neutron	electron	positron	α particle

- In balancing any nuclear equation, we must balance *the total of all atomic numbers* and *the total of all mass numbers* for the products and reactants

$${}^{226}_{88}\mathrm{Ra} \longrightarrow {}^{222}_{86}\mathrm{Rn} + {}^{4}_{2}\mathrm{He}$$

$${}^{6}_{3}\mathrm{Li} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{3}_{1}\mathrm{H} + {}^{4}_{2}\mathrm{He}$$

Nuclear Equations

- Example:

  Identify X in the following nuclear equation:

$${}^{78}_{33}\mathrm{As} \longrightarrow {}^{A}_{Z}\mathrm{X} + {}^{0}_{-1}\beta$$

Σ reactant mass numbers = Σ product mass numbers

$78 = A + 0$

$A = 78$

Σ reactant atomic numbers = Σ product atomic numbers

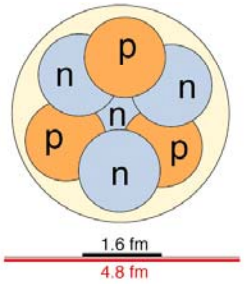
$33 = Z + (-1)$

$Z = 34$

Therefore, X is Se or ${}^{78}_{34}\mathrm{Se}$

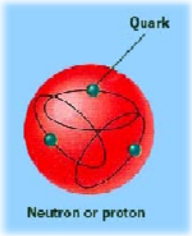
Nuclear Facts

- Some facts about the nucleus:
    - It occupies a very small portion of the atom. “the radius of an atom is more than 10,000 times the radius of the nucleus”
    - It contains most of the mass of the atom because it contains the heavy components of the atoms, i.e. protons and neutrons.
    - Its density is approximately 2×10^{14} g/cm^3.
    - There is an extremely strong force that holds the subnuclear particles together. This results with a very high energy stored in the nucleus. *“Nuclear stability”*



Nuclear Stability

- Nuclear stability is determined by a balance between two opposing forces:
    1. the Coulombic repulsions between protons.
    2. the nuclear force “also called short-range nuclear attractions” which is very strong and takes place between proton-proton, proton-neutron, and neutron-neutron.



If repulsions > attractions, the nucleus is unstable.

If attractions > repulsions, the nucleus is stable.

Neutron-to-Proton Ratio

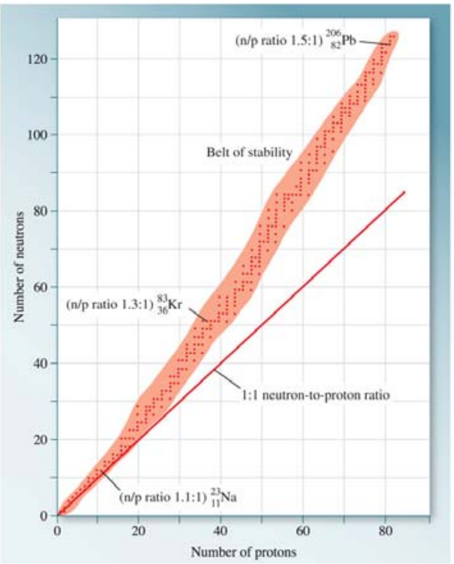
- ***n/p*** is the neutron-to-proton ratio.
  - The closer the value of *n*/*p* to 1, the more stable the nucleus. This is the case for elements having atomic numbers $Z \leq 20$.
  - As *Z* increases, the *n*/*p* ratio increases.

    Why?

    Because at higher atomic numbers, the repulsion between protons becomes more significant. Thus, more neutrons are needed to overcome the strong repulsion between the protons.

Belt of Stability

- *Stable nuclei* are located within the region of the belt of stability.
- *Radioactive nuclei* are located outside the belt of stability.
- As *Z* increases, the *n*/*p* ratio increases.



Useful Rules for Nuclear Stability

1. Nuclei that contain a *magic number* of protons and/or neutrons are stable.
    - *Magic numbers* are 2, 8, 20, 50, 82 and 126.
2. Nuclei with *even numbers* of both protons and neutrons are more stable than nuclei with odd numbers of protons and neutrons.

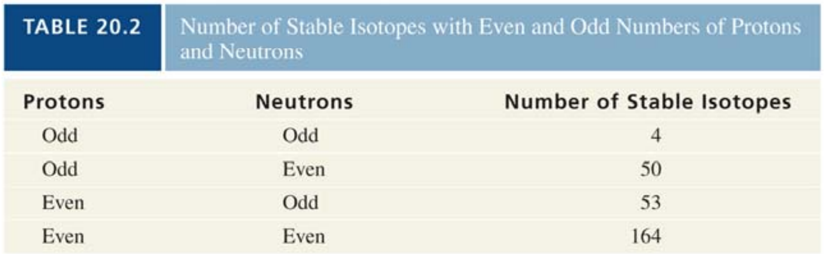


TABLE 20.2 Number of Stable Isotopes with Even and Odd Numbers of Protons and Neutrons

Protons	Neutrons	Number of Stable Isotopes
Odd	Odd	4
Odd	Even	50
Even	Odd	53
Even	Even	164

Useful Rules for Nuclear Stability

3. All isotopes of the elements with atomic numbers *higher than 83* are radioactive.
4. All isotopes of technetium (Tc, $Z = 43$) and promethium (Pm, $Z = 61$) are radioactive.

Belt of Stability

For the region ***above the belt***, the nucleus tends to lower the *n*/*p* ratio.

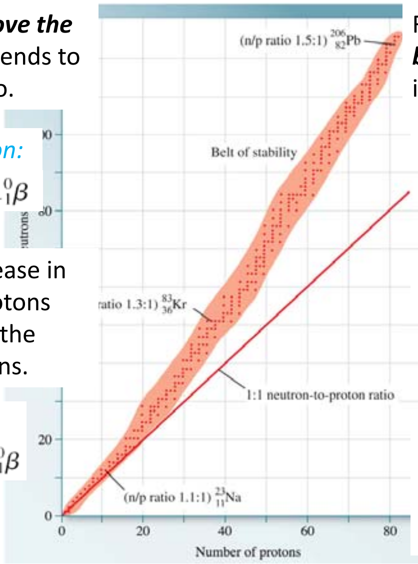
β-particle emission:

$${}^{1}_{0}\text{n} \longrightarrow {}^{1}_{1}\text{p} + {}^{0}_{-1}\beta$$

It leads to an increase in the number of protons and a decrease in the number of neutrons.

Example:

$${}^{14}_{6}\text{C} \longrightarrow {}^{14}_{7}\text{N} + {}^{0}_{-1}\beta$$



For the region ***below the belt***, the nucleus tends to increase the *n*/*p* ratio.

Positron emission:

$${}^{1}_{1}\text{p} \longrightarrow {}^{1}_{0}\text{n} + {}^{0}_{+1}\beta$$

$${}^{38}_{19}\text{K} \longrightarrow {}^{38}_{18}\text{Ar} + {}^{0}_{+1}\beta$$

Electron capture:

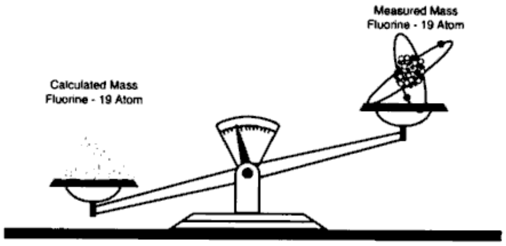
$${}^{1}_{1}\text{p} + {}^{0}_{-1}e \longrightarrow {}^{1}_{0}\text{n}$$

$${}^{37}_{18}\text{Ar} + {}^{0}_{-1}e \longrightarrow {}^{37}_{17}\text{Cl}$$

They lead to a decrease in the number of protons and an increase in the number of neutrons.

Nuclear Binding Energy

- The ***nuclear binding energy*** is the energy required to break up a nucleus into its component protons and neutrons.
- It represents the conversion of mass to energy which occurs during an exothermic nuclear reaction.
- The *measured* masses of atoms are always *less* than the *calculated* sum of masses of neutrons, protons and electrons. This is known as the ***mass defect***.



20.2

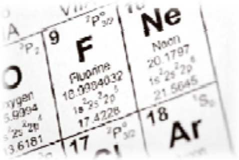
Nuclear Binding Energy

Consider the $^{19}_{9}\text{F}$ isotope. Its measured mass is 18.9984 amu.

Using the following masses:

$^{1}_{1}\text{H}$ = 1.007825 amu

$^{1}_{0}n$ = 1.008665 amu



Mass of an $^{19}_{9}\text{F}$ atom can be calculated:

$$\underbrace{9 \times 1.007825 \text{ amu}}_{\text{Mass of 9 protons and 9 electrons}} + \underbrace{10 \times 1.008665 \text{ amu}}_{\text{Mass of 10 neutrons}} = \underset{\uparrow\ \textit{Mass defect}}{19.15708 \text{ amu}}$$

- According to *relativity theory*, the loss in mass shows up as energy (heat) that is given off by the nucleus (*exothermic* process).

20.2

Nuclear Binding Energy

- We can calculate the energy released upon formation of the F isotope in the previous example.

Einstein equation:

$$\Delta E = (\Delta m)c^2$$

$$\Delta E = E \text{ (products)} - E \text{ (reactants)}$$

$$\Delta m = m \text{ (products)} - m \text{ (reactants)}$$

$$\Delta m = 18.9984 \text{ amu} - 19.15708 \text{ amu} = -0.1587 \text{ amu}$$

$$\Delta m = -0.1587 \text{ amu} \times \frac{1.00 \text{ kg}}{6.022 \times 10^{26} \text{ amu}} = -2.635 \times 10^{-26} \text{ kg}$$

c : the speed of light (3.00×10^{8} m/s)

Nuclear Binding Energy

$\Delta E = (-\,2.635 \times 10^{-26}\ \text{kg})(3.00 \times 10^{8}\ \text{m/s})^2$

$= (-\,2.37 \times 10^{-11}\ \text{kg·m}^2/\text{s}^2)$

$= (-\,2.37 \times 10^{-11}\ \text{J})$ *Exothermic*

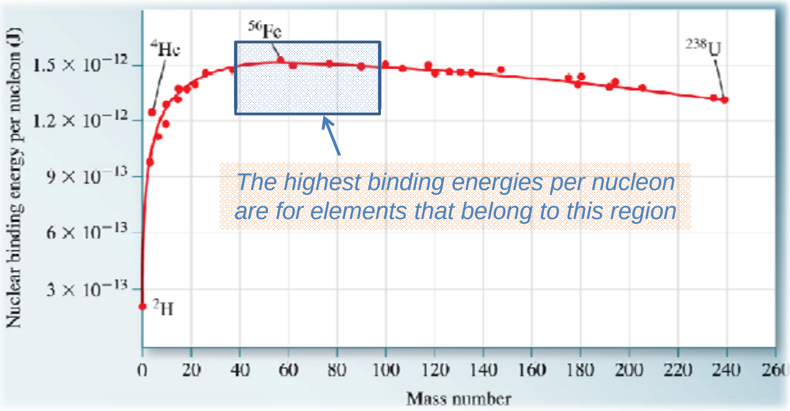
$= (-\,2.37 \times 10^{-11}\ \text{J})\ (6.022 \times 10^{23}\ /\text{mol}) = -\,1.43 \times 10^{10}\ \text{kJ/mol}$

- Therefore, the nuclear binding energy for 1 mole of F-19 nuclei is 1.43×10^{10} kJ.

  Compare this with the enthalpy for the combustion of methane (890.4 kJ per mole of CH_4).

  Nuclear binding energies are extremely large compared to the energies associated with ordinary chemical reactions.

Nuclear Binding Energy

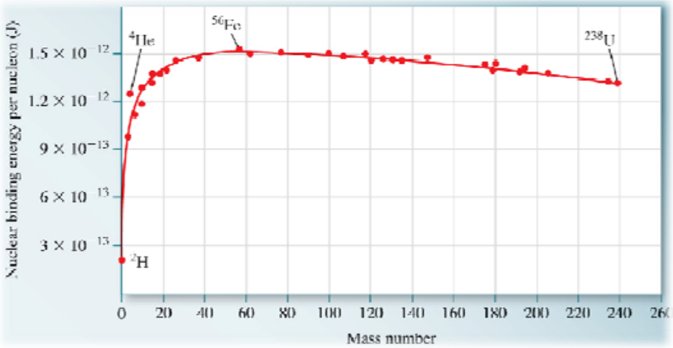


The highest binding energies per nucleon are for elements that belong to this region

- Nuclear binding energy per nucleon = $\dfrac{\text{nuclear binding energy}}{\text{number of nucleons}}$

number of protons plus neutrons

Nuclear Binding Energy



- Nuclear binding energy per nucleon = $\frac{\text{nuclear binding energy}}{\text{number of nucleons}}$

For F-19, the nuclear binding energy per nucleon = $\frac{2.37 \times 10^{-11}\ \text{J}}{19\ \text{nucleons}}$ = 1.25×10^{-12} J/nucleon

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Nuclear Binding Energy

- Exercise:
  Calculate:
  a) the nuclear binding energy in kJ/mol, and
  b) the nuclear binding energy in joules per nucleon of $^{208}_{83}\text{Bi}$.
  The exact atomic mass of bismuth is 208.9804 amu.

Mass of 83 protons and 83 electrons: $83 \times 1.007825 = 83.649475\,\text{amu}$

Mass of 10 neutrons: $125 \times 1.008665 = 126.083125\,\text{amu}$

Calculated mass : 209.732600 amu

$$\Delta m = 208.9804\ \text{amu} - 209.732600\ \text{amu} = -0.7522\ \text{amu}$$

$$\Delta m = (-0.7522\ \text{amu})\left(\frac{1.00\ \text{kg}}{6.022 \times 10^{26}\ \text{amu}}\right) = 1.2491 \times 10^{-27}\ \text{kg}$$

20.2

Nuclear Binding Energy

$$\Delta E = \left(-1.2491\times10^{-27}\ \text{kg}\right)\left(3.00\times10^{8}\ \text{m/s}\right)^2$$

$$\Delta E = -1.12\times10^{-10}\ \text{kg m}^2/\text{s}^2 = -1.12\times10^{-10}\ \text{J}$$

$$\Delta E = \left(-1.12\times10^{-10}\ \text{J}\right)\left(6.022\times10^{23}/\text{mol}\right)$$

$$\Delta E = -6.74\times10^{13}\ \text{J/mol} = -6.74\times10^{13}\ \text{kJ/mol}$$ *"Exothermic"*

$$\text{Nuclear binding energy} = 6.74\times10^{13}\ \text{kJ/mol}$$

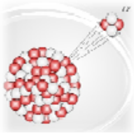
b) Nuclear binding energy per nucleon.

$$\Delta E = \frac{1.12\times10^{-10}\ \text{J}}{208\ \text{nucleons}} = 5.38\times10^{-13}\ \text{J/nucleon}$$

20.3

Nuclear Radioactivity

- ***Radioactivity*** is a spontaneous emission of *particles* and/or *electromagnetic radiation* by chemical elements (like those with an atomic number greater than 83, or those that lie outside the belt of stability). These elements (or nuclei) are called ***radioactive***.

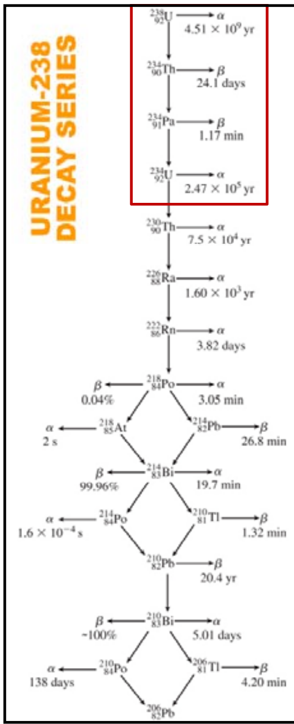


- Types of radioactive emission:

^1_1H or ^1_1p	^1_0n	$^{\ 0}_{-1}e$ or $^{\ 0}_{-1}\beta$	$^{\ 0}_{+1}e$ or $^{\ 0}_{+1}\beta$	$^4_2\alpha$ or $^4_2\text{He}^{2+}$
proton	neutron	electron	positron	α particle

γ rays

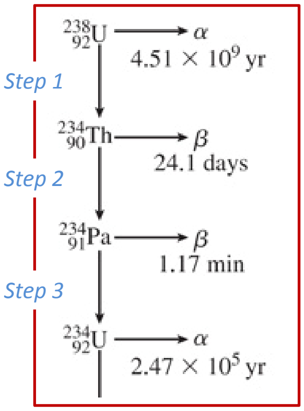
Electromagnetic radiation with very short wavelength (0.1 – 104 nm)



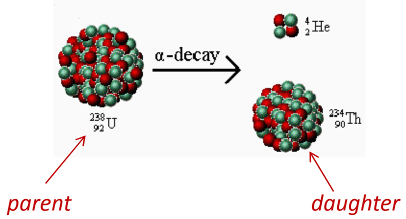
Nuclear Radioactivity

- The ***radioactive decay series*** is a *sequence* of nuclear reactions (nuclear decay or *disintegration*) that result in the formation of a stable isotope.
- The scheme of the a radioactive decay series usually shows the *half-lives* of all the nuclear decay steps involved.
- Each step in the series must be balanced in terms of protons and neutrons.

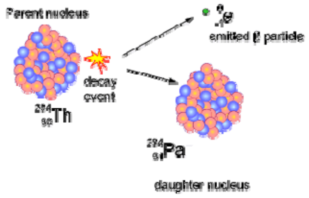
Nuclear Radioactivity



Step 1: $^{238}_{92}U \rightarrow \, ^{234}_{90}Th + \, ^{4}_{2}\alpha$



Step 2: $^{234}_{90}Th \rightarrow \, ^{234}_{91}Pa + \, ^{0}_{-1}\beta$



Kinetics of Radioactive Decay

- For a particular radioactive nuclide, the ***rate of decay*** can be expressed as:

$$\text{rate} = \left(-\frac{\Delta N}{\Delta t}\right)$$

where N is the number of nuclides in a given sample

1000 atoms of a certain nuclides $\xrightarrow{\textit{1 minute}}$ 990 atoms remained unchanged

10 atoms decayed

The rate of decay will be: $\left(-\dfrac{1000 - 990 \text{ atoms}}{60 \text{ s}}\right)$

Kinetics of Radioactive Decay

- The rate of decay is *directly* proportional to the number of nuclides (N) in a given sample:

$$\text{rate} = \left(-\frac{\Delta N}{\Delta t}\right) \ \alpha \ N$$

$$\text{rate} = \left(-\frac{\Delta N}{\Delta t}\right) = kN$$

← *The rate law of a 1st order process*

Thus, all radioactive decays are assumed to *obey 1st order kinetics*.

- The integrated 1st order rate law is:

$$\ln \frac{N_t}{N_0} = -kt$$

N_0 : The original number of nuclides (at $t = 0$)

N_t : The number of remaining nuclides at time t

k : The rate constant of radioactive decay of that given nuclide.

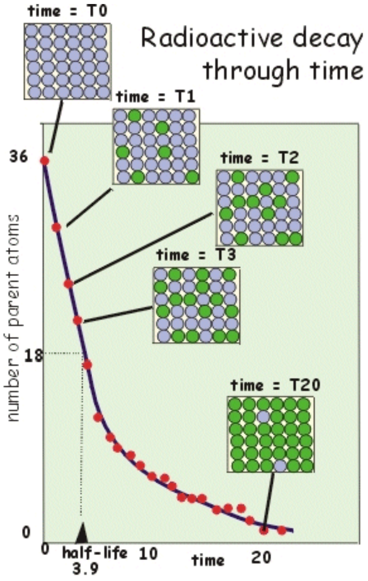
Half-life of Radioactive Decay

- The ***half-life*** ($t_{1/2}$) of a radioactive sample is the time required for the number of nuclides to reach half the original value.

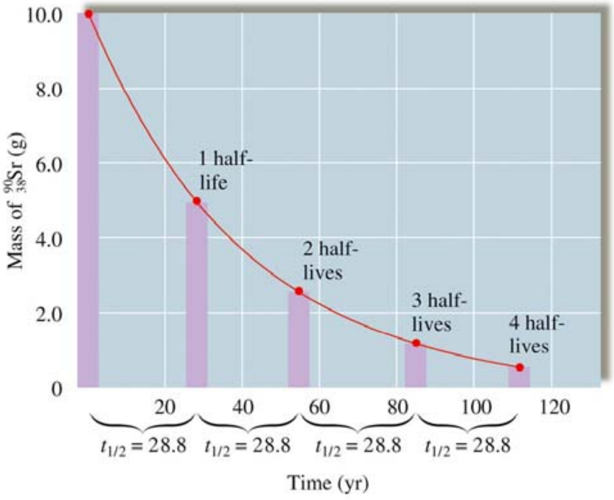
$$t_{1/2} = \frac{0.693}{k}$$

The half-life of a 1st order process

Thus, rate constants of different radioactive decays processes are different.



Half-life of Radioactive Decay



The decay of a 10.0-g sample of strontium-90 over time.

Half-life of Radioactive Decay

TABLE 18.3 The Half-Lives of Nuclides in the $^{238}_{92}U$ Decay Series

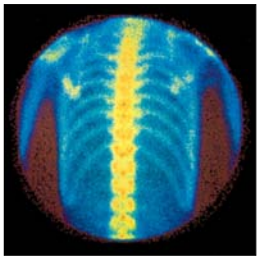
Nuclide	Particle Produced	Half-Life	$k = \frac{0.693}{t_{1/2}}$
Uranium-238 ($^{238}_{92}U$) ↓	α	4.51×10^9 years	1.53×10^{-10} yr^{-1}
Thorium-234 ($^{234}_{90}Th$) ↓	β	24.1 days	0.0288 day^{-1}
Protactinium-234 ($^{234}_{91}Pa$) ↓	β	6.75 hours	0.103 hr^{-1}
Uranium-234 ($^{234}_{92}U$) ↓	α	2.48×10^5 years	
Thorium-230 ($^{230}_{90}Th$) ↓	α	8.0×10^4 years	
Radium-226 ($^{226}_{88}Ra$) ↓	α	1.62×10^3 years	
Radon-222 ($^{222}_{86}Rn$) ↓	α	3.82 days	

The rate constant of a radioactive decay process is independent of environmental conditions, such as pressure and temperature.

Half-life of Radioactive Decay

- Example:

  Technetium-99 (Tc) is used to form pictures of internal organs in the body, such as bones and the heart. The rate constant of the decay of Tc is known to be 1.16×10^{-1} h^{-1}. What is the half-life of this isotope?



$$t_{1/2} = \frac{0.693}{k}$$

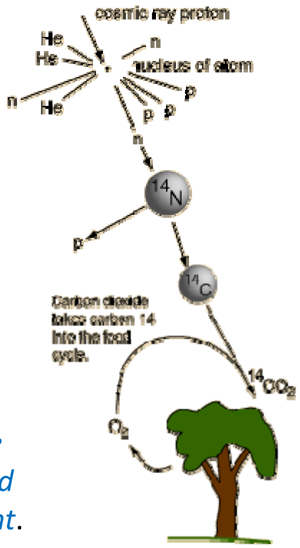
$$= \frac{0.693}{1.16 \times 10^{-1}\ \text{h}^{-1}} = 5.98\ \text{h}$$

Dating Based on Radioactivity Decay

- Half-lives of radioactive isotopes "usually *known as atomic clocks*" are used to determine the age of several materials such as rocks, dead humans and animals, and ancient objects.
- This measurement is called ***radioactive dating***.

Archaeologists routinely use radioactive decays to determine the age of ancient and historical materials and artifacts.

C-14 Radioactive Decay



- C-14 is continuously produced in the atmosphere by nuclear transmutation of N-14.

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

- Also, C-14 continuously decomposes by transmitting β- particles.

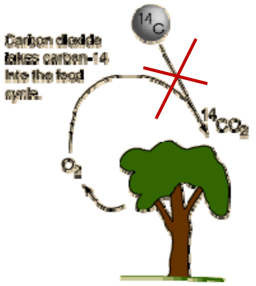
$${}^{14}_{6}\text{C} \rightarrow {}^{14}_{7}\text{N} + {}^{0}_{-1}\beta$$

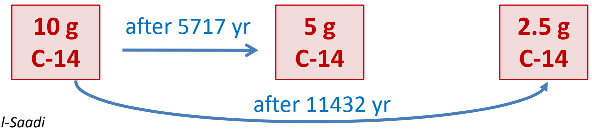
- Over years, the rates of the above two processes have become equal. Thus, *the ratio of C-14/C-12 in the atmosphere and in living matters remains almost constant*.

Dating Based on C-14 Radioactive Decay

$$^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\beta \qquad t_{1/2} = 5715 \text{ yr}$$

- When the living matter (human, plant, animal, etc.) dies, C-14 inside it continue to decay without replenishment, as it doesn't breath anymore.
- Comparing the C-14/C-12 ratio of a dead matter with the ration of a living matter gives information about the age of that particular matter.





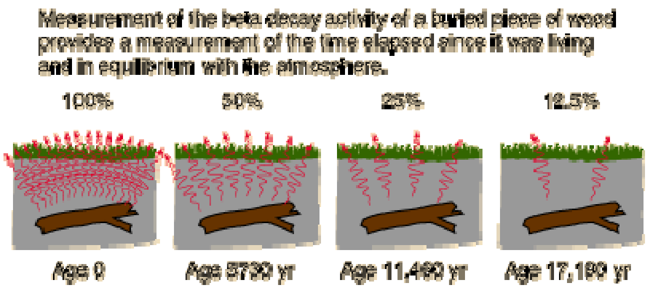
10 g C-14 → after 5717 yr → **5 g C-14**

10 g C-14 → after 11432 yr → **2.5 g C-14**

Dating Based on C-14 Radioactive Decay

- In practice, the decay activity of C-14 in the old object is compared with the corresponding one in a living object.

  The activity is measured in units of (*disintegrations per second*).



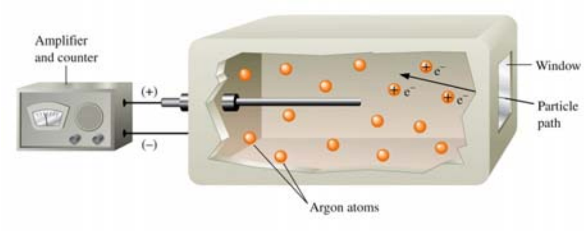
Measurement of the beta decay activity of a buried piece of wood provides a measurement of the time elapsed since it was living and in equilibrium with the atmosphere.

Dating Based on C-14 Radioactive Decay

- In practice, the decay activity of C-14 in the old object is compared with the corresponding one in a living object.

  The activity is measured in units of (disintegrations per second).

Geiger-Müller counter



Dating Based on C-14 Radioactive Decay

- <u>Exercise:</u>
  A piece of linen cloth found at an ancient burial site is found to have a ^{14}C activity of 4.8 disintegrations per minute. Determine the age of the cloth. Assume that the carbon-14 activity of an equal mass of living flax (the plant from which linen is made) is 14.8 disintegrations per minute. The half-life of carbon-14 is 5715 years.

Dating Based on Uranium-238 Radioactive Decay

- C-14 can be used to predict the age of archaeological objects dating back 1000 to 50,000 years, but not older than that.

  For older objects (rocks and extraterrestrial objects), uranium-238 is used because of its very long half-live.

$$^{238}_{92}\text{U} \rightarrow\ ^{234}_{90}\text{Th} +\ ^{4}_{2}\alpha \qquad t_{1/2} = 4.51 \times 10^{9}\ \text{yr}$$

- The half-life of U-238 is the longest ever-known half-life. The second longest half-life is that associated with the decay of U-234 to Th-230.

$$^{234}_{92}\text{U} \rightarrow\ ^{230}_{90}\text{Th} +\ ^{4}_{2}\alpha \qquad t_{1/2} = 2.47 \times 10^{5}\ \text{yr}$$

$t_{1/2}$ (U-238 → Th-234) is about 20,000 times $t_{1/2}$ (U-234 → Th-230)

Dating Based on Uranium-238 Radioactive Decay

238
U
92

- Since the decay of U-238 is of an extremely long $t_{1/2}$ compared to other decaying processes, *we will assume that the U-238 → Pb-206 decaying process has the same half-live as for U-238 → Th-234 process*.

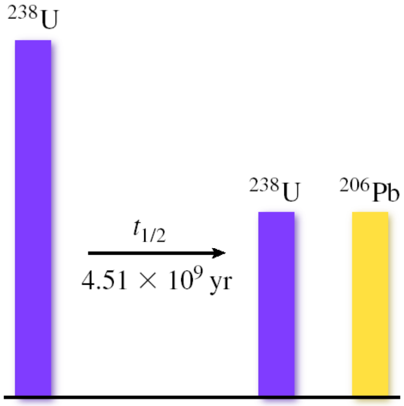
$$^{238}_{92}\text{U} \rightarrow\ ^{206}_{82}\text{Pb} + 8\ ^{4}_{2}\alpha + 6\ ^{4}_{-1}\beta \qquad t_{1/2} = 4.51 \times 10^{9}\ \text{yr}$$

- Thus, for any old sample, the ratio of Pb-206 to U-238 should give information about the age of that sample.

☞An analysis of a piece of rock shows that it contains 0.50 mol of Pb-206 and 0.50 mol of U-238. Assuming that when that piece of rock was initially formed, it had only U-238 and had no Pb-206. *What do you conclude about the age of that rock?*

Dating Based on Uranium-238 Radioactive Decay

$^{238}_{92}\text{U} \rightarrow \, ^{206}_{82}\text{Pb} + 8\,^{4}_{2}\alpha + 6\,^{4}_{-1}\beta$ $t_{1/2} = 4.51 \times 10^{9}$ yr



We conclude that that rock is approximately 4.5×10^{9} years.

The mass ratio ^{206}Pb/^{238}U is:
(206 g /2) / (238 g /2) = 0.866

- Ratios less than 0.866 => the rocks are less than 4.5×10^{9} years old.
- Ratios greater than 0.866 => the rocks are more than 4.5×10^{9} years old.

Dating Based on Uranium-238 Radioactive Decay

- Exercise:

  Determine the age of a rock that contains 12.75 mg of ^{238}U and 1.19 mg of ^{206}Pb.

Nuclear Transmutation

- Nuclear transmutation differs from *natural* radioactive decay in that the radioactive species is prepared by the *collision* of two particles.
- The first transmutation experiment was carried out by Rutherford in 1919 to produce O-17 isotope.

$${}^{14}_{7}\text{N} + {}^{4}_{2}\alpha \rightarrow {}^{17}_{8}\text{O} + {}^{1}_{1}\text{H}$$

The transmutation process shown above can be abbreviated as:

$${}^{14}_{7}\text{N}\ (\alpha,\text{p})\ {}^{17}_{8}\text{O}$$

bombarding particle

emitted particle

Nuclear Transmutation

- Exercise:

  Write the equation for the process represented by:

$${}^{106}_{46}\text{Pd}(\alpha,\text{p}){}^{109}_{47}\text{Ag}$$

bombarding particle

emitted particle

$${}^{106}_{46}\text{Pd} + {}^{4}_{2}\text{He} \rightarrow {}^{109}_{47}\text{Ag} + {}^{1}_{1}\text{p}$$

Transuranium Elements

- ***Transuranium elements*** are those elements with atomic numbers greater than 92.

TABLE 20.3 Preparation of the Transuranium Elements

Atomic Number	Name	Symbol	Preparation*
93	Neptunium	Np	${}^{238}_{92}\text{U} + {}^{1}_{0}\text{n} \longrightarrow {}^{239}_{93}\text{Np} + {}^{0}_{-1}\beta$
94	Plutonium	Pu	${}^{239}_{93}\text{Np} \longrightarrow {}^{239}_{94}\text{Pu} + {}^{0}_{-1}\beta$
95	Americium	Am	${}^{239}_{94}\text{Pu} + {}^{1}_{0}\text{n} \longrightarrow {}^{240}_{95}\text{Am} + {}^{0}_{-1}\beta$
96	Curium	Cm	${}^{239}_{94}\text{Pu} + {}^{4}_{2}\alpha \longrightarrow {}^{242}_{96}\text{Cm} + {}^{1}_{0}\text{n}$
97	Berkelium	Bk	${}^{241}_{95}\text{Am} + {}^{4}_{2}\alpha \longrightarrow {}^{243}_{97}\text{Bk} + 2{}^{1}_{0}\text{n}$
98	Californium	Cf	${}^{242}_{96}\text{Cm} + {}^{4}_{2}\alpha \longrightarrow {}^{245}_{98}\text{Cf} + {}^{1}_{0}\text{n}$
99	Einsteinium	Es	${}^{238}_{92}\text{U} + 15{}^{1}_{0}\text{n} \longrightarrow {}^{253}_{99}\text{Es} + 7{}^{0}_{-1}\beta$
100	Fermium	Fm	${}^{238}_{92}\text{U} + 17{}^{1}_{0}\text{n} \longrightarrow {}^{255}_{100}\text{Fm} + 8{}^{0}_{-1}\beta$
101	Mendelevium	Md	${}^{253}_{99}\text{Es} + {}^{4}_{2}\alpha \longrightarrow {}^{256}_{101}\text{Md} + {}^{1}_{0}\text{n}$
102	Nobelium	No	${}^{246}_{96}\text{Cm} + {}^{12}_{6}\text{C} \longrightarrow {}^{254}_{102}\text{No} + 4{}^{1}_{0}\text{n}$
103	Lawrencium	Lr	${}^{252}_{98}\text{Cf} + {}^{10}_{5}\text{B} \longrightarrow {}^{257}_{103}\text{Lr} + 5{}^{1}_{0}\text{n}$
104	Rutherfordium	Rf	${}^{249}_{98}\text{Cf} + {}^{12}_{6}\text{C} \longrightarrow {}^{257}_{104}\text{Rf} + 4{}^{1}_{0}\text{n}$

Transuranium Elements

- Transuranium elements are synthesized with the help of ***particle accelerators***.

105	Dubnium	Db	${}^{249}_{98}\text{Cf} + {}^{15}_{7}\text{N} \longrightarrow {}^{260}_{105}\text{Db} + 4{}^{1}_{0}\text{n}$
106	Seaborgium	Sg	${}^{249}_{98}\text{Cf}+ {}^{18}_{8}\text{O} \longrightarrow {}^{263}_{106}\text{Sg} + 4{}^{1}_{0}\text{n}$
107	Bohrium	Bh	${}^{209}_{83}\text{Bi} + {}^{54}_{24}\text{Cr} \longrightarrow {}^{262}_{107}\text{Bh} + {}^{1}_{0}\text{n}$
108	Hassium	Hs	${}^{208}_{82}\text{Pb} + {}^{58}_{26}\text{Fe} \longrightarrow {}^{265}_{108}\text{Hs} + {}^{1}_{0}\text{n}$
109	Meitnerium	Mt	${}^{209}_{83}\text{Bi} + {}^{58}_{26}\text{Fe} \longrightarrow {}^{266}_{109}\text{Mt} + {}^{1}_{0}\text{n}$
110	Darmstadtium	Ds	${}^{208}_{82}\text{Pb} + {}^{62}_{28}\text{Ni} \longrightarrow {}^{269}_{110}\text{Ds} + {}^{1}_{0}\text{n}$
111	Roentgenium	Rg	${}^{209}_{83}\text{Bi} + {}^{64}_{28}\text{Ni} \longrightarrow {}^{272}_{111}\text{Rg} + {}^{1}_{0}\text{n}$
112	Ununbium	Uub	${}^{208}_{82}\text{Pb} + {}^{70}_{30}\text{Zn} \longrightarrow {}^{277}_{112}\text{Uub} + {}^{1}_{0}\text{n}$
113	Ununtrium	Uut	${}^{288}_{115}\text{Uup} \longrightarrow {}^{284}_{113}\text{Uut} + {}^{4}_{2}\alpha$
114	Ununquadium	Uuq	${}^{244}_{94}\text{Pu} + {}^{48}_{20}\text{Ca} \longrightarrow {}^{289}_{114}\text{Uuq} + 3{}^{1}_{0}\text{n}$
115	Ununpentium	Uup	${}^{243}_{95}\text{Am} + {}^{48}_{20}\text{Ca} \longrightarrow {}^{288}_{115}\text{Uup} + 3{}^{1}_{0}\text{n}$
116	Ununhexium	Uuh	${}^{248}_{96}\text{Cm} + {}^{48}_{20}\text{Ca} \longrightarrow {}^{292}_{116}\text{Uuh} + 4{}^{1}_{0}\text{n}$
118	Ununoctium	Uuo	${}^{249}_{98}\text{Cf} + {}^{48}_{20}\text{Ca} \longrightarrow {}^{294}_{118}\text{Uuo} + 3{}^{1}_{0}\text{n}$

Synthesis of Isotopes

- Radioactive isotopes can be prepared by using:
  - *Neutrons as projectiles.*

    It is a convenient approach because there will be no repulsion between the neutrons and nuclei.

    $$^{6}_{3}\text{Li} + ^{1}_{0}\text{n} \rightarrow ^{3}_{1}\text{H} + ^{4}_{2}\alpha$$

  - *Protons or α particles as projectiles.*

    It requires considerable kinetic energy to overcome the electrostatic potential between the positively charged particles and nuclei. Thus, *particle accelerators* are essential for this approach of isotope synthesis.

    $$^{27}_{13}\text{Al} + ^{4}_{2}\alpha \rightarrow ^{30}_{15}\text{P} + ^{1}_{0}\text{n}$$

Particle Accelerators

A ***particle accelerator*** is a very long tube (1 to 5 km) that is used to accelerate bombarding particles up to 90% of the speed of light so they can smash the nuclei and break them into fragments.