Nuclear Chemistry

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Objectives

At the end of this, we will be able to-

- Know about the radioactive elements and properties of radiations and nuclear reactions
- Explain the rate of radioactive decays and half life period of radioisotopes
- Apply the concepts in radioactive dating

Contents

- Radioactive elements
- Properties of alpha, beta and gamma rays
- Radioactive decay
- Calculation of half-life period of radioactive isotope
- Radioactive dating
- Nuclear reaction.

Radioactivity & Nuclear Chemistry- Introduction

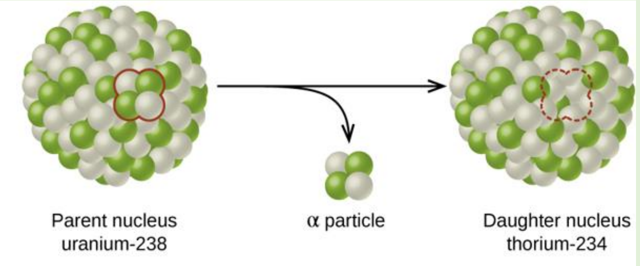
Atomic theory in the nineteenth century presumed that nuclei had fixed compositions.

But in 1896, the French scientist Henri Becquerel found that a uranium compound placed near a photographic plate made an image on the plate, even if the compound was wrapped in black cloth.

He reasoned that the uranium compound was emitting some kind of radiation that passed through the cloth to expose the photographic plate.

Further investigations showed that the radiation was a combination of particles and electromagnetic rays, with its ultimate source being the atomic nucleus. These emanations were ultimately called, collectively, radioactivity.

Following the somewhat serendipitous discovery of radioactivity by Becquerel, many prominent scientists began to investigate this new, intriguing phenomenon. Among them were Marie Curie (the first woman to win a Nobel Prize, and the only person to win two Nobel Prizes in different sciences—chemistry and physics), who was the first to coin the term "radioactivity," and Ernest Rutherford (of gold foil experiment fame), who investigated and named three of the most common types of radiation. During the beginning of the twentieth century, many radioactive substances were discovered, the properties of radiation were investigated and quantified, and a solid understanding of radiation and nuclear decay was developed.



The spontaneous change of an unstable nuclide into another is radioactive decay. The unstable nuclide is called the parent nuclide; the nuclide that results from the decay is known as the daughter nuclide. The daughter nuclide may be stable, or it may decay itself. The radiation produced during radioactive decay is such that the daughter nuclide lies closer to the band of stability than the parent nuclide, so the location of a nuclide relative to the band of stability can serve as a guide to the kind of decay it will undergo.

Radioactivity & Types of Radioactive Decay

The term radioactivity was proposed by Marie Curie to describe the emission of ionizing radiation by some of the heavier elements.

Ionizing radiation, as the name implies, interacts with matter to produce ions. This means that the radiation is sufficiently energetic to break chemical bonds. Some ionizing radiation is particulate (consisting of particles), and some is nonparticulate.

Alpha Particles (α)

Alpha particles are the nuclei of helium-4 atoms, $^4He^{2+}$ ejected spontaneously from the nuclei of certain radioactive atoms. This emission is a process in which a bundle of two protons and two neutrons is emitted by a radioactive nucleus, resulting in a lighter nucleus. Alpha particles produce large numbers of ions via their collisions and near collisions with atoms as they travel through matter, but their penetrating power is low. (Generally, a few sheets of paper can stop them.) Because they have a positive charge, particles are deflected by electric and magnetic fields. We can represent the production of particles by means of a nuclear equation,

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

- Balancing:
  - mass number: $238 = 234 + 4$
  - atomic number: $92 = 90 + 2$

The **atomic number** identifies the product, i.e., 90 is Th (thorium)

The sum of mass numbers must be the same on both sides.
The sum of atomic numbers must be the same on both sides

Radioactivity & Types of Radioactive Decay

Beta Particles (β^-)

Beta particles are deflected by electric and magnetic fields in the opposite direction from α particles. They are less massive than α particles, so they are deflected more strongly than α particles. They have a greater penetrating power through matter than do particles (a book, rather than just a few sheets of paper, may be required to stop them). β particles are electrons, but they are electrons that originate from the nuclei of atoms in nuclear decay processes and are therefore extremely energetic. Electrons that surround the nucleus are given the familiar symbol, e^-.The simplest decay process producing a particle is the decay of a free neutron, which is unstable outside the nucleus of an atom.

A β^- particle does not have an atomic number, but its 1- charge is equivalent to an atomic number of -1. In nuclear equations, the β^- particle is represented as $^{0}_{-1}\beta$.

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

Also, a β^- particle is small enough, compared to protons and neutrons, that its mass can be ignored in most calculations. The symbol v represents an entity called a neutrino. This particle was first postulated in the 1930s as necessary for the conservation of certain properties during the β^- decay process. Because they interact so weakly with matter, neutrinos were not detected until the 1950s For a typical β^- decay process, a neutron within the nucleus of an atom spontaneously converting to a proton and an electron. This proton remains in the nucleus, whereas the electron is emitted as a β^- particle. Because of the extra proton, the atomic number increases by one unit, while the mass number is unchanged. **The elusive neutrino is generally not included in the nuclear equation.**

Beta emission: $^{131}_{53}I \rightarrow {}^{131}_{54}Xe + {}^{0}_{-1}e$

- Balancing:
  - atomic number: $53 = 54 + (-1)$
  - mass number: $131 = 131 + 0$

In a similar manner, in some decay processes a proton within the nucleus is converted to a neutron, and a β^+ particle and a neutrino* are emitted.

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

The β^+ particle, also called a positron, has properties similar to the β^- particle, except that it carries a positive charge. This particle is also known as a positive electron and is designated $^{0}_{+1}\beta$ in nuclear equations.

Positron emission is commonly encountered with artificially produced radioactive nuclei of the lighter elements.

$$^{30}_{15}P \longrightarrow {}^{30}_{14}Si + {}^{0}_{+1}\beta$$

Radioactivity& Types of Radioactive Decay

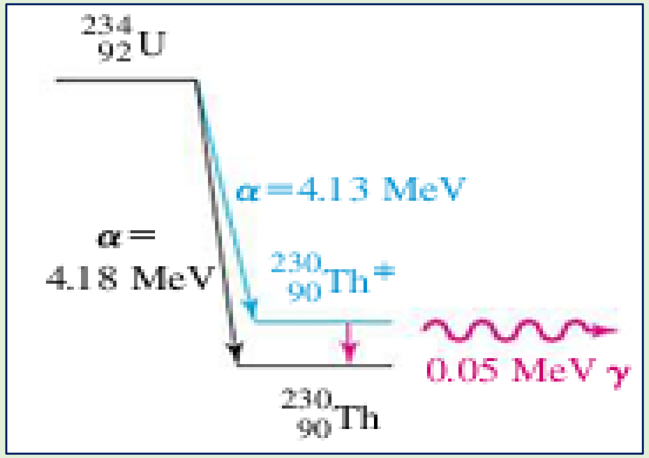
Gamma Rays

Some radioactive decay processes that yield α or β^- particles leave the nucleus in an excited state. The nucleus then loses energy in the form of electromagnetic radiation called gamma rays, γ. Gamma (γ) rays are a highly penetrating form of radiation that are undeflected by electric and magnetic fields. (Lead bricks more than several centimeters thick may be required to stop them.) In the radioactive decay of $^{234}_{92}\mathrm{U}$, 77% of the nuclei emits α particles having an energy of 4.18 MeV. The remaining 23% of the $^{234}_{92}\mathrm{U}$ nuclei produce α particles with energies of 4.13 MeV. In the latter case, the $^{230}_{90}\mathrm{Th}$ nuclei are left with an excess energy of 0.05 MeV. This energy is released as γ rays. The unstable excited Th nucleus is denoted as $^{230}_{90}\mathrm{Th}^{\ddagger}$ we can write,

$$^{234}_{92}\mathrm{U} \longrightarrow {}^{230}_{90}\mathrm{Th}^{\ddagger} + {}^{4}_{2}\mathrm{He}$$

$$^{230}_{90}\mathrm{Th}^{\ddagger} \longrightarrow {}^{230}_{90}\mathrm{Th} + \gamma$$

This γ mission process is represented diagrammatically



Production of γ rays
The transition of a $^{230}_{90}\mathrm{Th}$ nucleus between the two energy states shown results in the emission of 0.05 MeV of energy in the form of γ rays.

An electronvolt (eV) is the energy acquired by an electron when it falls through an electric potential difference of 1 volt:

$$1\ \mathrm{eV} = 1.6022 \times 10^{-19}\ \mathrm{J}$$
$$1\ \mathrm{MeV} = 1 \times 10^{6}\ \mathrm{eV}$$

Electron Capture

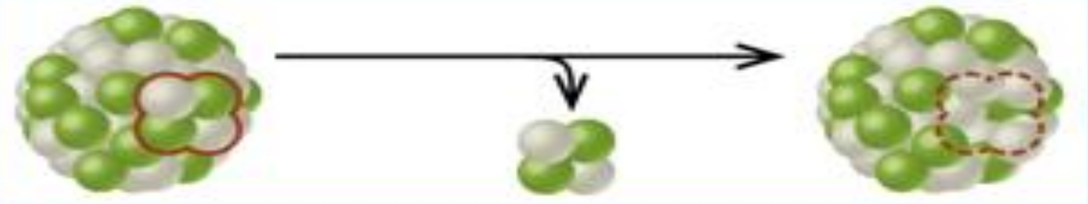
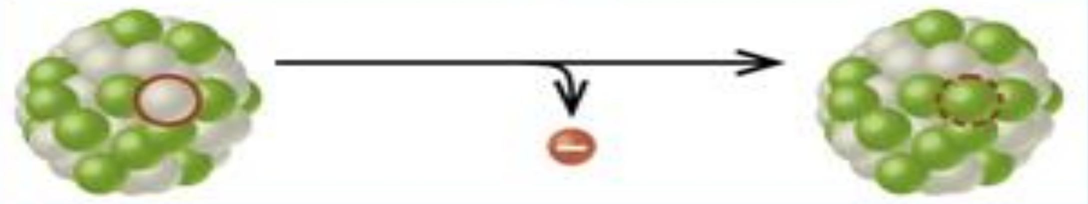
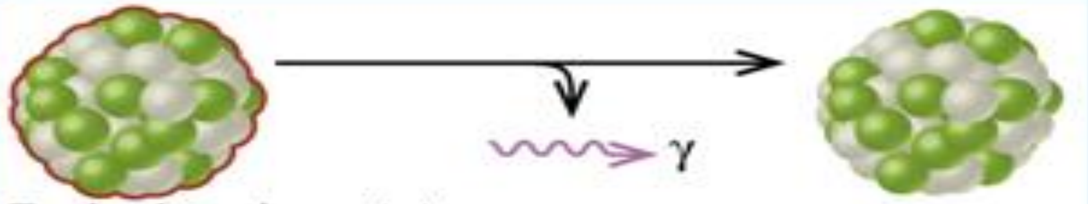
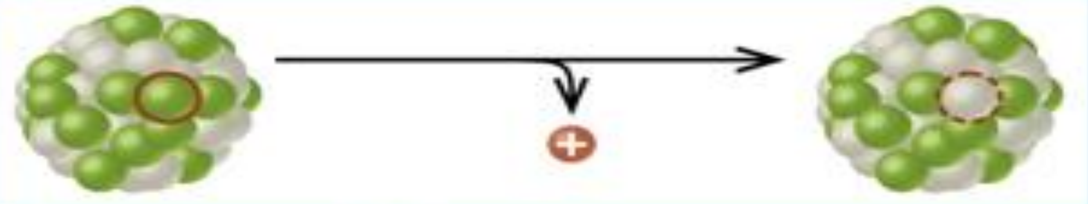
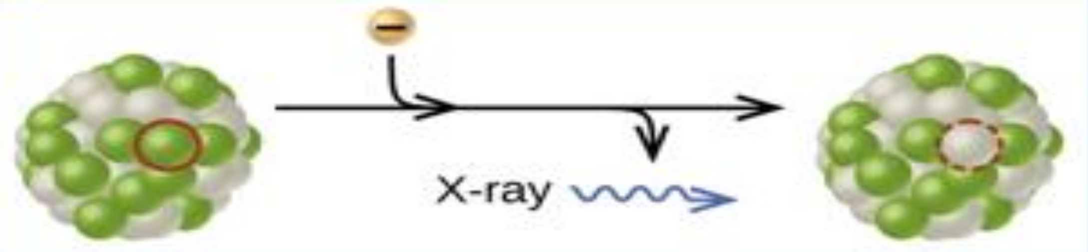
A process that achieves the same effect as positron emission is electron capture (EC). In this case, an electron from an inner electron shell (usually the shell n =1) is absorbed by the nucleus, where it converts a proton to a neutron. When an electron from a higher quantum level drops to the energy level vacated by the captured electron, X radiation is emitted. For example,

$$^{81}_{37}\mathrm{Rb} + {}^{0}_{-1}\mathrm{e} \rightarrow {}^{81}_{36}\mathrm{Kr}$$

Balancing:
- atomic number: $37 + (-1) = 36$
- mass number: $81 + 0 = 81$

$$^{202}_{81}\mathrm{Tl} + {}^{0}_{-1}\mathrm{e} \longrightarrow {}^{202}_{80}\mathrm{Hg}\ \text{(followed by X radiation)}$$

Radioactivity& Types of Radioactive Decay

Type	Nuclear equation	Representation	Change in mass/atomic numbers
Alpha decay	$^{A}_{Z}X \quad ^{4}_{2}He + ^{A-4}_{Z-2}Y$		A: decrease by 4 Z: decrease by 2
Beta decay	$^{A}_{Z}X \quad ^{0}_{-1}e + ^{A}_{Z+1}Y$		A: unchanged Z: increase by 1
Gamma decay	$^{A}_{Z}X \quad ^{0}_{0}\gamma + ^{A}_{Z}Y$	 Excited nuclear state	A: unchanged Z: unchanged
Positron emission	$^{A}_{Z}X \quad ^{0}_{+1}e + ^{A}_{Z-1}Y$		A: unchanged Z: decrease by 1
Electron capture	$^{A}_{Z}X \quad ^{0}_{-1}e + ^{A}_{Z-1}Y$		A: unchanged Z: decrease by 1

Radioactivity& Types of Radioactive Decay

Write nuclear equations to represent (a) α-particle emission by ^{222}Rn and (b) radioactive decay of bismuth-215 to polonium-215.

(a) Since the $^{222}_{86}Rn$ nucleus ejects an α particle, $^{4}_{2}He$, as shown in the following incomplete nuclear equation.

$$^{222}_{86}Rn \longrightarrow ? + ^{4}_{2}He$$

Because the ejected α particle contains two protons, the unknown product must contain two fewer protons than $^{222}_{86}Rn$: $Z = 86 - 2 = 84$. This atomic number identifies the element as polonium, $_{84}Po$. The mass number (A) of the product can be obtained by subtracting the mass number of the α particle from that of the radon isotope: $A = 222 - 4 = 218$. The completed nuclear equation is

$$^{222}_{86}Rn \longrightarrow ^{218}_{84}Po + ^{4}_{2}He$$

(b) The atomic number of bismuth is 83 and that of polonium is 84. We can approach this problem as we did part **(a)**.

$$^{215}_{83}Bi \longrightarrow ^{215}_{84}Po + ?$$

There is no change in mass number, so the particle has a zero mass number. Its atomic number is $Z = 83 - 84 = -1$. Only a $^{0}_{-1}\beta$ particle fits these parameters: Beta ($-$) decay is the only type of emission leading to an increase of one unit in atomic number without a change in the mass number.

$$^{215}_{83}Bi \longrightarrow ^{215}_{84}Po + ^{0}_{-1}\beta$$

A nuclear equation for the production of ^{56}Mn by bombardment of ^{59}Co with neutrons

The unknown particle must have A = 4 and Z = 2; a it is an α particle.

$$^{59}_{27}Co + ^{1}_{0}n \longrightarrow ^{56}_{25}Mn + ^{4}_{2}He$$

Naturally Occurring Radioactive Isotopes

Of the stable nuclides, ^{209}Bi has the highest atomic number and mass number. All known nuclides beyond it in atomic and mass numbers are radioactive.

Nuclide is the general term for an atom with a particular atomic number and mass number. Different nuclides of an element are referred to as isotopes.

Naturally occurring ^{238}U is radioactive and disintegrates the loss of α particles.

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

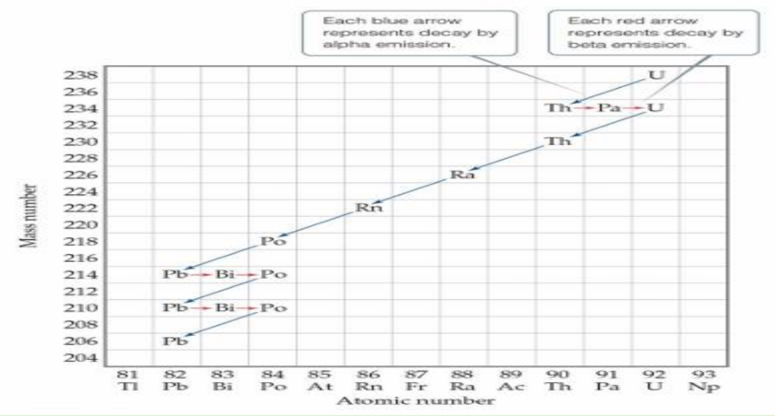
^{234}Th is also radioactive; it decays by β^- emission. ^{234}Pa is also decays by β^- emission to produce ^{234}U, which is also radioactive.

$$^{234}_{90}Th \longrightarrow {}^{234}_{91}Pa + {}^{0}_{-1}\beta$$

$$^{234}_{91}Pa \longrightarrow {}^{234}_{92}U + {}^{0}_{-1}\beta$$

The term daughter is commonly used to describe the new nuclide produced in a radioactive decay. ^{234}Th is the daughter of ^{238}U, ^{234}Pa is the daughter of ^{234}Th and so on. The chain of radioactive decay that begins with ^{238}U continues through a number of steps of α and β^- emission until it eventually terminates with a stable isotope of lead- ^{206}Pb.

All naturally occurring radioactive nuclides of high atomic number belong to one of three radioactive decay series: the uranium series, the thorium series, or the actinium series. (The actinium series actually begins with uranium-235, which was once called actino-uranium.) Even though some of the daughters in natural radioactive decay schemes have very short half-lives, all are present because they are constantly forming as well as decaying. It is likely that only about one gram of radium-226 was present in several tons of uranium ore processed by Marie Curie in her discovery of radium in 1898. Nevertheless, she was successful in isolating it. The ore also contained only a fraction of a milligram of polonium, which she was able to detect but not isolate. Radioactive decay schemes can be used to determine the ages of rocks and thereby the age of Earth. The appearance of certain radioactive substances in the environment can also be explained through radioactive decay series. The nuclides ^{210}Po and ^{210}Pb have been detected in cigarette smoke. These radioactive isotopes are derived from ^{238}U, found in trace amounts in the phosphate fertilizers used in tobacco fields. These α-emitting isotopes have been implicated in the link between cigarette smoking and cancer and heart disease.



The natural radioactive decay series for ^{234}U. The long arrows pointing down and to the left correspond to α emissions. The short horizontal arrows represent β particle emissions. Other natural decay series originate with ^{232}Th (thorium series) and ^{235}U (actinium series)

Naturally Occurring Radioactive Isotopes

Radioactivity of lighter elements

Radioactivity is relatively rare phenomenon among the naturally occurring lighter isotopes. Even so, ^{40}K is a radioactive isotope, as are ^{50}V, and ^{138}La. ^{40}K decays by β^- emission and by electron capture.

$$^{40}_{19}\mathrm{K} \longrightarrow {}^{40}_{20}\mathrm{Ca} + {}^{0}_{-1}\beta \qquad {}^{40}_{19}\mathrm{K} + {}^{0}_{-1}\mathrm{e} \longrightarrow {}^{40}_{18}\mathrm{Ar}$$

At the time Earth was formed ^{40}K decays was much more abundant than it is now. It is believed that the high argon content of the atmosphere (0.934% by volume and almost all of it as ^{40}Ar) is derived from the radioactive decay of ^{40}K. Aside from ^{40}K, and ^{14}C (produced by cosmic radiation), the most important radioactive isotopes of the lighter elements are produced artificially.

Induced Radioactivity

Ernest Rutherford discovered that atoms of one element can be transformed into atoms of another element. He did this in 1919 by bombarding $^{14}{}_{7}N$ with α particles, producing $^{17}{}_{8}O$ nuclei and protons.

$$^{14}_{7}\mathrm{N} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{17}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{H}$$

^{17}O is a naturally occurring nonradioactive isotope of oxygen (0.037% natural abundance).

In 1934, when bombarding aluminum with α particles, Iréne Joliot-Curie (daughter of Marie and Pierre Curie) and her husband, Frédéric Joliot, observed the emission of two types of particles: neutrons and positrons. The Joliots observed that when bombardment by α particles was stopped, the emission of neutrons also stopped; the emission of positrons continued, however. Their conclusion was that the nuclear bombardment of $^{30}{}_{15}P$ produces a radioactive decay by the emission of positrons.

$$^{27}_{13}\mathrm{Al} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{30}_{15}\mathrm{P} + {}^{1}_{0}\mathrm{n}$$
$$^{30}_{15}\mathrm{P} \longrightarrow {}^{30}_{14}\mathrm{Si} + {}^{0}_{+1}\beta$$

Transuranium Elements

Until 1940, the only known elements were those that occur naturally. In 1940, bombardment of ^{238}U atoms with neutrons produced the first synthetic element. First, the unstable nucleus $^{239}_{92}U$ forms. This nucleus then undergoes β^- decay, yielding the element neptunium, with Z = 93

$$^{238}_{92}U + {}^{1}_{0}n \longrightarrow {}^{239}_{92}U + \gamma$$
$$^{239}_{92}U \longrightarrow {}^{239}_{93}Np + {}^{0}_{-1}\beta$$

Bombardment by neutrons is an effective way to produce nuclear reactions because these heavy uncharged particles are not repelled as they approach a nucleus.

Since 1940, all the elements from Z = 93 to 112, as well as elements 114 and 116, have been synthesized. Many of the new elements of high atomic number have been formed by bombarding transuranium atoms with the nuclei of lighter elements.

For example, an isotope of the element Z = 105 induced by bombarding atoms of $^{249}_{98}Cf$ with $^{15}_{7}N$ nuclei.

$$^{249}_{98}Cf + {}^{15}_{7}N \longrightarrow {}^{260}_{105}Db + 4\,{}^{1}_{0}n$$

Nuclear reactions requires bombarding atomic nuclei with energetic particles. Such energetic particles can be obtained in an accelerator. A type of accelerator known as a cyclotron. A charged-particle accelerator, as the name implies, can produce only beams of charged particles (such as $^{1}_{1}H^{+}$) as projectiles.

In many cases, neutrons are most effective as projectiles for nuclear bombardment. The neutrons required can be generated through a nuclear reaction produced by a charged-particle beam. In the following reaction, $^{2}_{1}H$ represents a beam of deuterons (actually, $^{2}_{1}H^{+}$) from an accelerator.

$$^{9}_{4}Be + {}^{2}_{1}H \longrightarrow {}^{10}_{5}B + {}^{1}_{0}n$$

Another important source of neutrons for nuclear reactions is a nuclear reactor.

Rate of Radioactive Decay & Half Life

In time, we can expect every atomic nucleus of a radioactive nuclide to disintegrate, but it is impossible to predict when any one nucleus will do so. Although we cannot make predictions for a particular atom, we can use statistical methods to make predictions for a collection of atoms. Based on experimental observations, a radioactive decay law has been established.

The rate of disintegration of a radioactive material called the activity, A, or the decay rate is directly proportional to the number of atoms present.

$$\text{rate of decay} \propto N \quad \text{and} \quad \text{rate of decay} = A = \lambda N$$

The activity is expressed in atoms per unit time, such as atoms per second. N is the number of atoms in the sample being observed; λ is the decay constant, which has units of time^{-1}. Consider the case of a 1,000,000-atom sample disintegrating at the rate of 100 atoms per second. In such a case, $N = 1.0 \times 10^6$

$$\lambda = A/N = 100\ \text{atoms s}^{-1} / 1.0 \times 10^6\ \text{atom} = 1.0 \times 10^{-4}\ \text{s}^{-1}$$

Radioactive decay is a first-order process. To relate it to the first-order kinetics, the activity as corresponding to a rate of reaction, the decay constant, as corresponding to a rate constant. This correspondence can be carried further by writing an integrated radioactive decay law and a relationship between the decay constant and the half-life of the process-the length of time required for half of a radioactive sample to disintegrate.

In these equations, N_0 represents the number of atoms at some initial time (t = 0); N_t is the number of atoms at some later time, t; λ is the decay constant; and $t_{1/2}$ is the half-life. The half-life of a first-order process is a constant.

$$\ln\left(\frac{N_t}{N_0}\right) = -\lambda t$$

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

- If half the atoms of a radioactive sample disintegrate in 2.5 min, the number of atoms remaining will be reduced to one-fourth the original number in 5.0 min, one-eighth in 7.5 min, and so on. The shorter the half life, the larger the value of λ and the faster the decay process. Half-lives of radioactive nuclides range from extremely short to very long.
- There is also an energy barrier that confines nuclear particles to the nucleus, molecular collisions do not invest any energy in nuclear particles. Moreover, in radioactive decay, nuclear particles do not escape the nucleus by surmounting an energy barrier they tunnel through it. Thus, the rates of radioactive decay processes are independent of temperature.

Rate of Radioactive Decay & Half Life

The phosphorus isotope ^{32}P is used in biochemical studies to determine the pathways of phosphorus atoms in living organisms. Its presence is detected through its emission of β^- particles. (a) What is the decay constant for ^{32}P, expressed in the unit s^{-1}? (b) What is the activity of a 1.00 mg sample of ^{32}P (that is, how many atoms disintegrate per second)? (c) Approximately what mass of ^{32}P will remain in the original 1.00 mg sample after 57 days? (See Table) (d) What will be the rate of radioactive decay after 57 days (Half life of ^{32}P is 14.3 d)?

(a) We can determine λ from $t_{1/2}$ with equation (25.13). The first result we get has the unit d^{-1}. We must convert this unit to h^{-1}, min^{-1}, and s^{-1}.

$$\lambda = \frac{0.693}{14.3\text{ d}} \times \frac{1\text{ d}}{24\text{ h}} \times \frac{1\text{ h}}{60\text{ min}} \times \frac{1\text{ min}}{60\text{ s}} = 5.61 \times 10^{-7}\text{ s}^{-1}$$

(b) First, let us find the number of atoms, N, in 1.00 mg of ^{32}P.

$$N(^{32}\text{P atoms}) = 0.00100\text{ g} \times \frac{1\text{ mol }^{32}\text{P}}{32.0\text{ g}} \times \frac{6.022 \times 10^{23}\ ^{32}\text{P atoms}}{1\text{ mol }^{32}\text{P}}$$
$$= 1.88 \times 10^{19}\ ^{32}\text{P atoms}$$

Then, we can multiply this number by the decay constant to get the activity or decay rate.

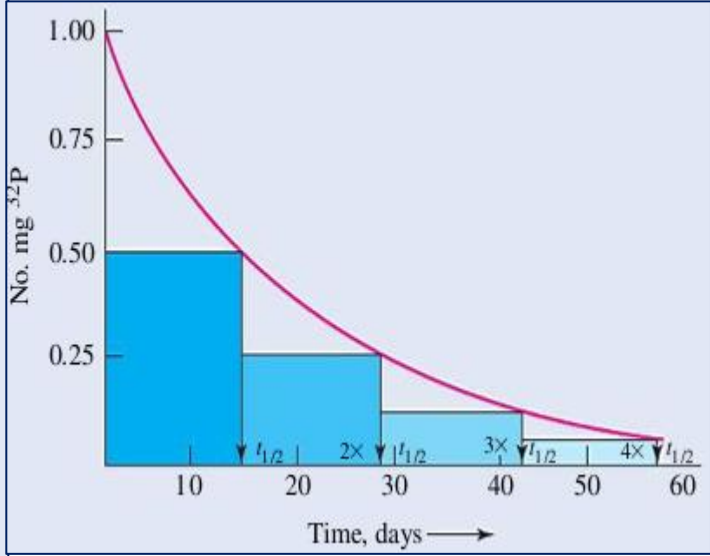
$$\text{activity} = \lambda N = 5.61 \times 10^{-7}\text{ s}^{-1} \times 1.88 \times 10^{19}\text{ atoms}$$
$$= 1.05 \times 10^{13}\text{ atoms/s}$$

(c) A period of 57 days is $57/14.3 = 4.0$ half-lives. As shown in Figure 25-4, the quantity of radioactive material decreases by one-half for every half-life. The quantity remaining is $\left(\frac{1}{2}\right)^4$ of the original quantity.

$$?\text{ mg }^{32}\text{P} = 1.00\text{ mg} \times \left(\frac{1}{2}\right)^4 = 1.00\text{ mg} \times \frac{1}{16} = 0.063\text{ mg }^{32}\text{P}$$

(d) The activity is directly proportional to the number of radioactive atoms remaining (activity $= \lambda N$), and the number of atoms is directly proportional to the mass of ^{32}P. When the mass of ^{32}P has dropped to one-sixteenth its original mass, the number of ^{32}P atoms also falls to one-sixteenth the original number, and the rate of decay is one-sixteenth the original activity.

$$\text{rate of decay} = \frac{1}{16} \times 1.05 \times 10^{13}\text{ atoms/s} = 6.56 \times 10^{11}\text{ atoms/s}$$



Radiocarbon Dating

In the upper atmosphere, $^{14}_{6}C$ is formed at a constant rate by the bombardment of $^{14}_{7}N$ with neutrons. The neutrons are produced by cosmic rays. $^{14}_{6}C$ disintegrates by β^- emission.

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

Carbon-containing compounds in living organisms are in equilibrium with $^{14}_{6}C$ in the atmosphere that is, these organisms replace $^{14}_{6}C$ atoms that have undergone radioactive decay with fresh atoms $^{14}_{6}C$ through interactions with their environment. The $^{14}_{6}C$ isotope is radioactive and has a half-life of 5730 years. The activity associated with $^{14}_{6}C$ that is in equilibrium with its environment is about 15 disintegrations per minute (dis min^{-1}) per gram of carbon. When an organism dies (for instance, when a tree is cut down), this equilibrium is destroyed, and the disintegration rate falls off because the dead organism no longer absorbs new $^{14}_{6}C$. From the measured disintegration rate at some later time, the age can be estimated (that is, the elapsed time since the $^{14}_{6}C$ equilibrium was disrupted).

A wooden object found in an Indian burial mound is subjected to radiocarbon dating. The activity associated with its $^{14}_{6}C$ is 10 dis min^{-1} g^{-1}. What is the age of the object? In other words, how much time has elapsed since the tree from which the wood came was cut down? Decay constant,

$$\lambda = \frac{0.693}{5730\ \text{y}} = 1.21 \times 10^{-4}\ \text{y}^{-1}$$

N_o at t = 0 (the time when the equilibrium was destroyed) and N_t at time t (the present time). The activity just before the $^{14}_{6}C$ equilibrium was destroyed was 15 dis min^{-1} g^{-1}; at the time of the measurement, it is 10 dis min^{-1} g^{-1}. The corresponding numbers of atoms are equal to these activities divided by λ.

$$N_0 = A_0/\lambda = 15/\lambda \quad \text{and} \quad N_t = A_t/\lambda = 10/\lambda$$

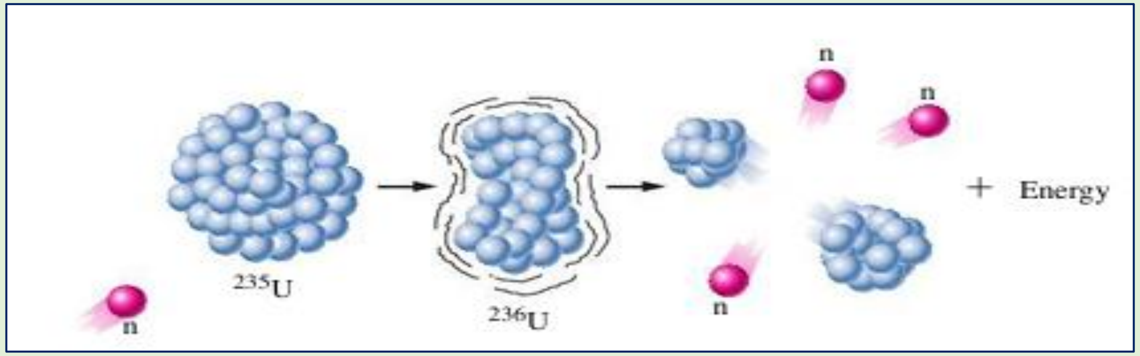
$$\ln\frac{N_t}{N_0} = \ln\frac{10/\lambda}{15/\lambda} = \ln\frac{10}{15} = -(1.21 \times 10^{-4}\ \text{y}^{-1})t$$

$$-0.41 = -(1.21 \times 10^{-4}\ \text{y}^{-1})t$$

$$t = \frac{0.41}{1.21 \times 10^{-4}\ \text{y}^{-1}} = 3.4 \times 10^{3}\ \text{y}$$

Nuclear Reactions- Fission & Fusion

Nuclear Fission In the process of fission, the nucleus of a heavy nuclide, such as ^{235}U, splits into two smaller fragments after being struck by a thermal neutron. Also released are two or three neutrons that can trigger the fission of other nuclei in a chain reaction. Essential components of a nuclear power reactor are the fissionable (fissile) nuclide, a moderator (such as water) to slow down the neutrons released during fission, control rods (such as cadmium) to control the fission by absorbing neutrons, and a heat-transfer medium (such as water).



Nuclear fission of ^{235}U with thermal neutrons

A neutron possessing ordinary thermal energy strikes ^{235}U . First, the unstable nucleus ^{236}U is produced; this then breaks up into a light fragment, a heavy fragment, and several neutrons. Various nuclear fragments are possible, but the most probable mass numbers are 97 for the light fragment and 137 for the heavy one.

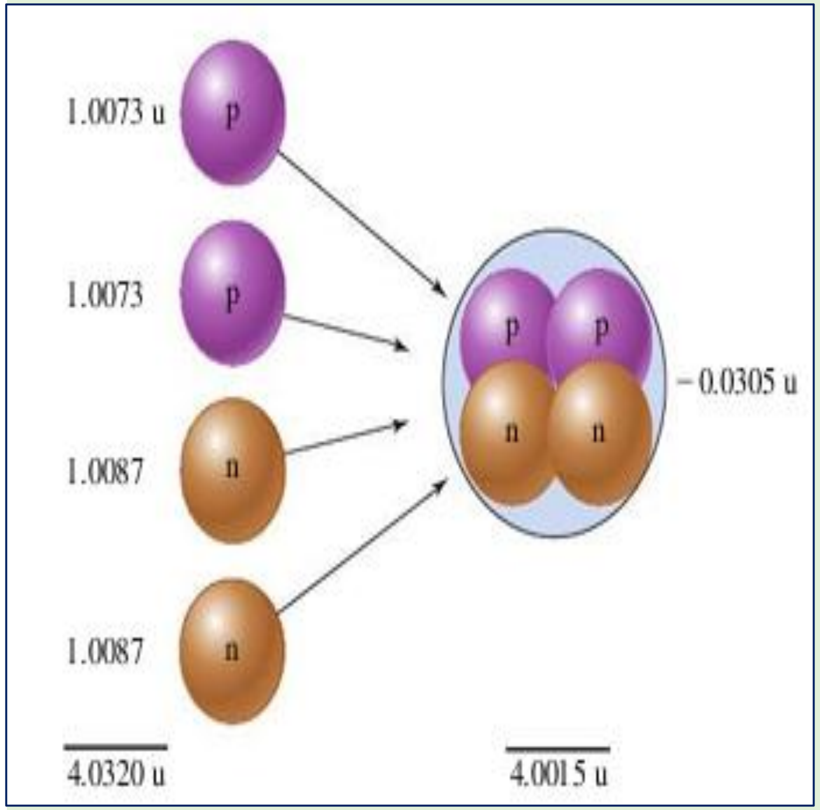
Nuclear Fusion The fusion of lighter nuclei into heavier ones converts small quantities of mass into enormous amounts of energy. This process occurs continuously in stars and in the hydrogen bomb. A controlled fusion reaction has yet to be achieved, but fusion research is being actively pursued because of the enormous potential of fusion as an energy source.

$$^{2}_{1}H + ^{3}_{1}H \longrightarrow ^{4}_{2}He + ^{1}_{0}n + \text{energy}$$

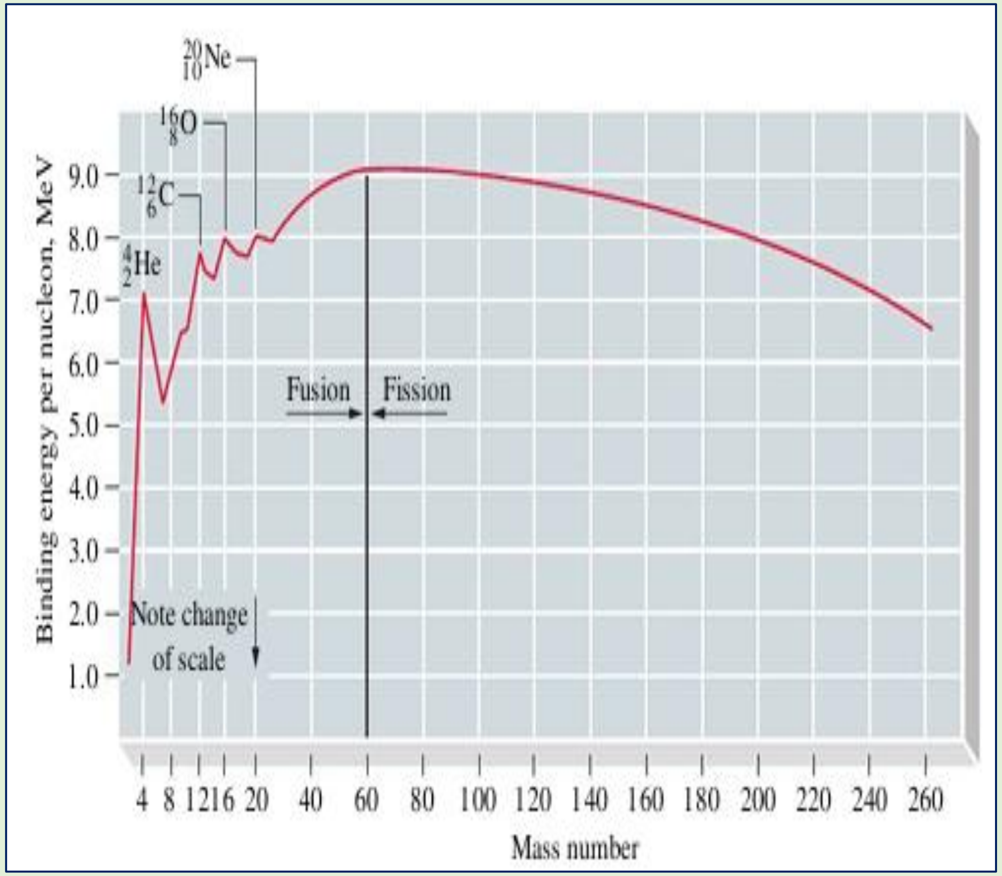
Energetics of Nuclear Reactions

Energetics of Nuclear Reactions

The energy changes in nuclear reactions are a consequence of Einsteins discovery of a mass energy equivalence. Nuclear binding energy is the energy released when nucleons fuse together into a nucleus; the lost mass is known as the mass defect. A plot of binding energy per nucleon versus mass number passes through a maximum at about A = 60. Thus, the fusion of nucleons is favored at lower mass numbers, and the fission of nuclei into lighter fragments is favored at higher mass numbers.



The mass of a helium nucleus ^4_2He is 0.0305 u (atomic mass unit) less than the combined masses of two protons and two neutrons. The energy equivalent to this loss of mass (called the mass defect) is the nuclear energy that binds the nuclear particles together.



Nuclear Stability

Nuclear Stability The stability of a nuclide depends on the ratio N/Z, on whether the numbers of neutrons (N) and protons (Z) are odd or even, and whether either is a magic number arising from nuclear shell theory. A plot of N versus Z shows that all stable nuclides lie within a belt of stability originating along the line N = Z, and expanding above the line at higher values of Z . Most radioactive nuclides lie outside the belt and undergo radioactive decay of a type that moves daughter nuclides into the belt.

Magic numbers

- 2, 8, 20, 28, 50, or 82 protons
- 2, 8, 20, 28, 50, 82, or 126 neutrons result in more stable nuclides

Smaller nuclei

- Proton/neutron ratio: 1:1

Larger nuclei

More protons– More repulsion– Need more Neutrons.

Belt of stability

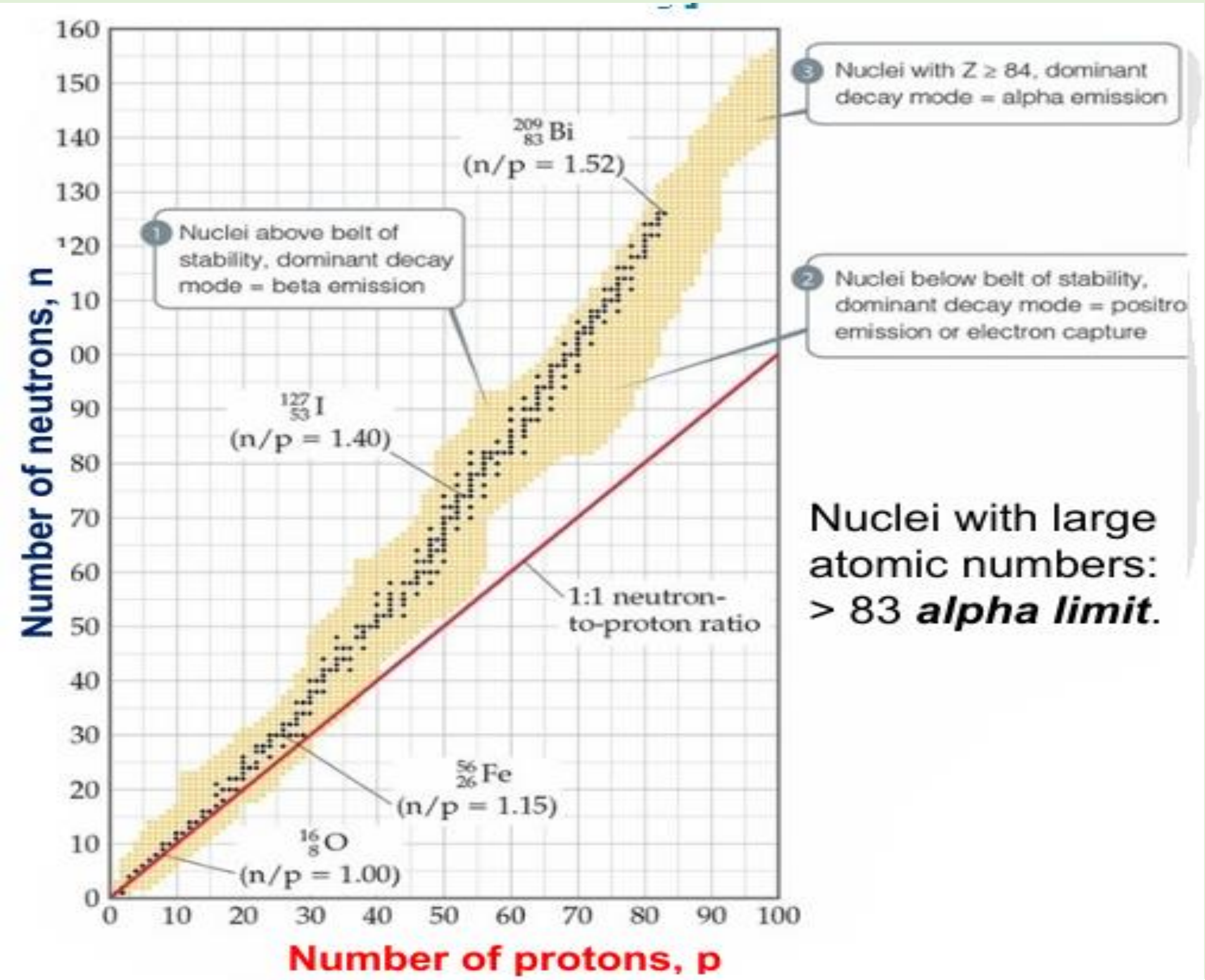
Zone of stability– It shows which nuclides would be stable.

Nuclei above the belt

- Have too many neutrons.
- Decay by beta emission
- Neutron -> proton + β^-

Nuclei below the belt

- Have too many protons.
- Usually decay by positron emission or electron capture.



Check List

1. Write a nuclear equation to represent β^- particle emission by $^{241}_{94}Pu$.
2. Write a nuclear equation to represent the decay of a radioactive nucleus to produce ^{58}Ni and a positron.
3. Write a nuclear equation for the production of ^{147}Eu by the bombardment of ^{139}La with ^{12}C.
4. Write a nuclear equation for the production ^{124}I by bombardment of ^{121}Sb with α particles. Also, write an equation for the subsequent decay of ^{124}I by positron emission.
5. The half-life of cobalt-60 is 5.27 year. How much of a 1.000-mg sample of cobalt-60 is left after 15.81 yr?
6. A rock contains 0.257 mg of lead-206 for every milligram of uranium 238. The half-life for the decay of uranium-238 to lead-206 is 4.5 X 10^9 yr. How old is the rock?
7. A wooden object from an archeological site is subjected to radiocarbon dating. The activity due to ^{14}C is measured to be 11.6 disintegrations per second. The activity of a carbon sample of equal mass from fresh wood is 15.2 disintegrations per second. The half-life of ^{14}C is 5730 yr. what is age of the archeological sample?