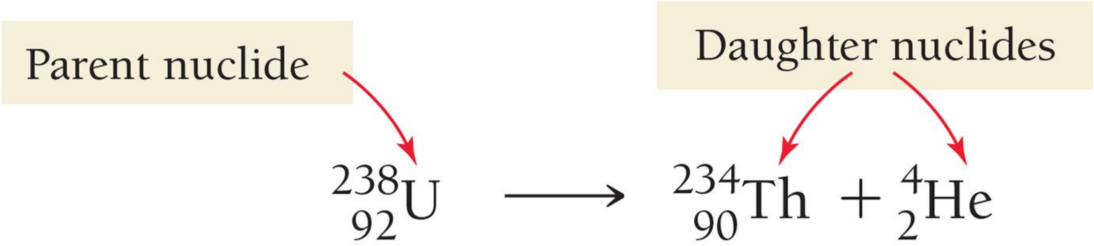
Chapter 2 :

Radioactivity :

Radioactivity is the spontaneous decomposition of atomic nuclei, which releases high-energy particles or rays. Many nuclei are radioactive; that is, they decompose by emitting particles and in doing so become a different nucleus.



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

In a balanced nuclear equation, both the atomic number and the mass number must be conserved.

I. Natural radioactivity :

Radioactivity was first discovered by Henri Becquerel in 1896. Later, Marie Curie studied the radiation of different compounds, and discovered that uranium and thorium are radioactive elements.

Every element has at least one isotope whose nucleus spontaneously decomposes (radioisotope).

A chemical element can therefore have both radioactive isotopes and non-radioactive isotopes. For example, carbon-12 is not radioactive, but carbon-14 is. Because radio-activity only affects the nucleus and not the electrons, the chemical properties of radioactive isotopes are the same as those of stable isotopes.

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

There is a different form of radioactivity that is harmful and not harmful. A certain level of radiation naturally occurs all around us, even in our bodies (potassium-40).

This process is also known as **radioactive decay**, or **radioactive disintegration**.

radioisotopes characterized by a very long half-life, such as uranium-238 (4.5 billion years) and potassium-40 (1.3 billion years). These have not had enough time to disintegrate completely since they were created.

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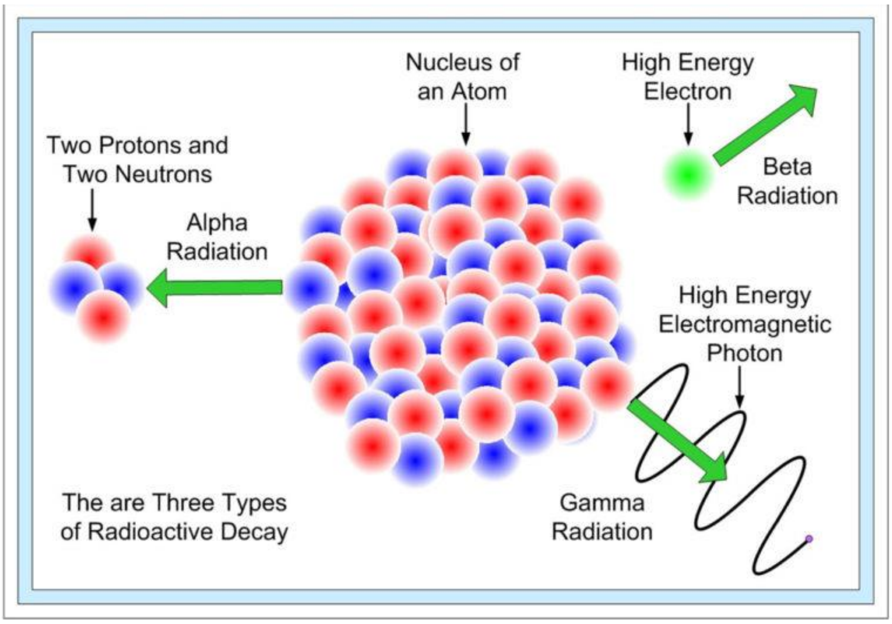
I.1. Types of radioactive radiation :

There are mainly three types of radioactive decay that were discovered first. All these types were named after the ability to penetrate matter. Later additional types of decay were discovered. The types of radioactive decays are as follows:



II.1.2. Alpha radiation :

Alpha radiation **(α)** is a heavy, very short-range particle and is actually an ejected helium nucleus He (A = 4, Z = 2).

$$^{A}_{Z}N_{1} \longrightarrow {}^{A-4}_{A-2}N_{2} + {}^{4}_{2}He\ ({}^{4}_{2}\alpha)$$

Example :

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

(Uranium)   (Thorium)

Some characteristics of alpha radiation are:

- ✓ Most alpha radiation is not able to penetrate human skin.
- ✓ Alpha-emitting materials can be harmful to humans if the materials are inhaled, swallowed, or absorbed through open wounds.
- ✓ Alpha radiation travels only a short distance (a few inches) in air, but is not an external hazard.
- ✓ Alpha radiation is not able to penetrate clothing.

Examples of some alpha emitters: radium, radon, uranium, thorium.

II.2.2. Beta radiation

Beta radiation is a light, short-range particle and is actually an ejected electron. Beta-decay (β) occurs with a nucleus having too many neutrons and too many protons; the protons or neutrons transform into another.

Beta radiation is again differentiated into two types - Beta minus (β^-) and Beta plus (β^+). Of which :

The change of a neutron to a proton, is accompanied by the **emission of a particle with negative electric charge**, namely an electron (a beta particle).

$${}^{1}_{0}n \longrightarrow {}^{1}_{1}p + {}^{0}_{-1}e\ (\beta^{-}) + {}^{0}_{0}\gamma$$

Neutron proton (négaton)

$${}^{A}_{Z}N_{1} \longrightarrow {}^{A}_{Z+1}N_{2} + {}^{0}_{1}e + {}^{0}_{0}\gamma$$

Example

$${}^{214}_{82}Pb \longrightarrow {}^{214}_{83}Bi + \beta^{-} + {}^{0}_{0}\gamma$$

Conversely a proton is converted into a neutron by the emission of a positron

$${}^{1}_{1}P \longrightarrow {}^{1}_{0}n + {}^{0}_{+1}e\ (\beta^{+}) + {}^{0}_{0}\gamma$$

Proton Neutron Positon

$${}^{A}_{Z}N_{2} \longrightarrow {}^{A}_{Z-1}N_{2} + {}^{0}_{+1}e + {}^{0}_{0}\gamma$$

<u>Example :</u>

$${}^{22}_{11}Na \longrightarrow {}^{22}_{10}Ne + \beta^{+} + {}^{0}_{0}\gamma$$

Some characteristics of beta radiation are:

- Beta radiation may travel several feet in air and is moderately penetrating.
- Beta radiation can penetrate human skin.
- Beta-emitting contaminants may be harmful if deposited internally.

Examples of some pure beta emitters: strontium-90, carbon-14, tritium, and sulfur-35.

I.2.3. Gamma radiation :

Gamma radiation consists of photons that originate from within the nucleus.

Some characteristics of these radiations are:

- Gamma radiation are able to travel many feet in air and many inches in human tissue. They readily penetrate most materials and are sometimes called "penetrating" radiation.
- Sealed radioactive sources and machines that emit gamma radiation constitute mainly an external hazard to humans.
- Gamma radiation frequently accompany the emission of alpha and beta radiation during radioactive decay.

  Examples of some gamma emitters: iodine-131, cesium-137, cobalt-60, radium-226, and technetium-99m.

II. artifecial radioactivity :

Known also as **nuclear transmutation,** results from the bombardment of nuclei by neutrons, protons, or other nuclei. An example of a nuclear transmutation is the conversion of atmospheric 147N to 14 6C and 1 1H,

In 1934, Irene Curie, the daughter of Pierre and Marie Curie, and her husband, Frederic Joliot, announced the first synthesis of an artificial radioactive isotope. They bombarded a thin piece of aluminum foil with α-particles produced by the decay of polonium and found that the aluminum target became radioactive. Chemical analysis showed that the product of this reaction was an isotope of phosphorus.

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

A shorthand notation has been developed for nuclear reactions such as the reaction discovered by Curie and Joliot. The parent (or target) nuclide and the daughter nuclide are separated by parentheses that contain the symbols for the particle that hits the target and the particle or particles released in this reaction.

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$$ {}^{27}_{13}Al(\alpha,n){}^{30}_{15}P $$

The nuclear reactions used to synthesize artificial radionuclides are characterized by enormous activation energies. Three devices are used to overcome these activation energies: linear accelerators, cyclotrons, and nuclear reactors. Linear accelerators or cyclotrons can be used to excite charged particles such as protons, electrons, α-particles, or even heavier ions, which are then focused on a stationary target. The following reaction, for example, can be induced by a cyclotron or linear accelerator.

$$ {}^{24}_{12}Mg + {}^{2}_{1}H \rightarrow {}^{22}_{11}Na + {}^{4}_{2}He $$

II.1. Nucleare reaction types :

A balanced nuclear reaction equation indicates that there is a rearrangement during a nuclear reaction, but subatomic particles are rearranged rather than atoms. Nuclear reactions also follow conservation laws, and they are balanced in two ways:

1. The sum of the **mass numbers** of the reactants equals the sum of the mass numbers of the products.
2. The sum of the **charges** of the reactants equals the sum of the charges of the products.

To discuss nuclear reactions in any depth, we need to understand how to write and balance the equations. Writing a nuclear equation differs somewhat from writing equations for chemical reactions. In addition to writing the symbols for various chemical elements, we must also explicitly indicate protons, neutrons, and electrons.

The symbols for elementary particles are as follows:

1. Helium type reactions :

- **(α, p)type reactions**

$$ {}^{4}_{2}\mathbf{He} + {}^{10}_{5}\mathbf{B} \longrightarrow {}^{1}_{1}\mathbf{H} + {}^{13}_{6}\mathbf{C}^{*} \quad \textbf{ou} \quad {}^{10}_{5}\mathbf{B}\,(\alpha,p)\ {}^{13}_{6}\mathbf{C}^{*} $$

- **(α, n) type reactions**

$$ {}^{4}_{2}\mathbf{He} + {}^{10}_{5}\mathbf{B} \longrightarrow {}^{13}_{7}\mathbf{N}^{*} + {}^{1}_{0}\mathbf{n} \quad \textbf{ou} \quad {}^{10}_{5}\mathbf{B}\,(\alpha,n)\ {}^{13}_{6}\mathbf{N}^{*} $$

*** Non-capture reactions (α particles are used as simple energy carriers, they cause the emission of protons without incorporating into the nucleus).**

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

2. (p) type reactions

- **(p,α) type réactions**

Protons have a high speed

$$ {}^{1}_{1}\mathbf{H} + {}^{14}_{7}\mathbf{N} \longrightarrow {}^{4}_{2}\mathbf{He} + {}^{11}_{6}\mathbf{C}^{*} \quad \textbf{or} \quad {}^{14}_{7}\mathbf{N}\,(p,\alpha)\ {}^{11}_{6}\mathbf{C}^{*} $$

$$ {}^{1}_{1}\mathbf{H} + {}^{7}_{3}\mathbf{Li} \longrightarrow \mathbf{2}\ {}^{4}_{2}\mathbf{He} \quad \textbf{or} \quad {}^{7}_{3}\mathbf{Li}\,(p,2\alpha) $$

- **(p,n) type réactions**

Protons having a high speed ($E_c \approx 200$à 10^3Mev)

$$ {}^{1}_{1}\mathbf{H} + {}^{63}_{29}\mathbf{Cu} \longrightarrow {}^{63}_{30}\mathbf{Zn} + {}^{1}_{0}\mathbf{n} \quad \textbf{ou} \quad {}^{30}_{29}\mathbf{Cu}\,(p,n)\ {}^{63}_{30}\mathbf{Zn} $$

We can have emission of several neutrons depending on the type of target and the speed of the projectile

$$ {}^{1}_{1}\mathbf{H} + {}^{209}_{83}\mathbf{Bi} \longrightarrow \mathbf{8}\ {}^{1}_{0}\mathbf{n} + {}^{202}_{84}\mathbf{Po} \quad \textbf{ou} \quad {}^{209}_{83}\mathbf{Bi}\,(p,8n)\ {}^{202}_{84}\mathbf{Po} $$

Protons having a low speed (slow protons): capture reaction

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

- **(p,d) type réactions:(rare)**

$$ {}^{1}_{1}\mathbf{H} + {}^{9}_{4}\mathbf{Be} \longrightarrow {}^{8}_{4}\mathbf{Be} + {}^{2}_{1}\mathbf{H} $$

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3. Reactions with the dentons(d)

$$^{2}_{1}\mathrm{H} + {}^{10}_{5}\mathrm{B} \longrightarrow \begin{cases} {}^{1}_{0}\mathrm{n} + {}^{11}_{6}\mathrm{C} \\ {}^{10}_{4}\mathrm{Be} + 2\,{}^{1}_{1}\mathrm{H} \\ 3\,{}^{4}_{2}\mathrm{He} \end{cases}$$

c) Reactions with neutrons (n)

- **Réactions avec capture**

$$^{79}_{35}\mathrm{Br} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{80}_{35}[\mathrm{Br}]^{*} \longrightarrow {}^{80}_{36}\mathrm{Kr} + {}^{0}_{-1}\beta$$

$$^{238}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{239}_{92}[\mathrm{U}]^{*} \longrightarrow {}^{239}_{93}\mathrm{Kr} + {}^{0}_{-1}\beta$$

This capture reaction will allow the synthesis of transuranians including Z>92

- **(n,p) type reactions**

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

- **(n, p) type reactions**

It is a bombardment of heavy nuclei, which causes the infected nucleus to explode into 2 or more medium-sized nuclei with a large power output. We have nuclear fission with neutron production.

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{143}_{56}\mathrm{Ba} + {}^{83}_{36}\mathrm{Kr} + 10\ {}^{1}_{0}\mathrm{n}$$

III. Bilan énergétique d’une réaction nucléaire :

Nuclear reactions involve considerable energies.

The energy obeys Einstein's fundamental law $E = \Delta M.c^{2}$, so it will be enough to determine Δ M to know the energy involved.

$\Delta M = \Sigma\, M\text{reactive} - \Sigma\, M\text{products}$

In the case where $\Delta M < 0$; there is an increase in mass → the reaction is called endoenergetic (the reaction requires an energy input).

In the case where $\Delta M > 0$ there is a decrease in mass $\longrightarrow$ the reaction is called exoenergetic (the reaction releases energy).

IV. radioactive family ;

76 different natural radioactive isotopes are known today, the largest part of it lies in the 4 natural decay series. These are the thorium series, uranium series, neptunium series and actinium series (or uranium-235 series). The neptunium series, startig with ^{237}Np, does not exist anymore because of the shorter half-life of $2.1 \cdot 10^6$ years of Neptunium compared to the age of the earth all the isotopes in this series have decayed.

- Decay series include α-, ß- and γ-decays

- they can have branches but always end with the same final product

- Cascades of radioactive decays which origin from a certain radioactive nuclide and ends with a certain stable nuclide (lead or bismuth)

$$X^* \longrightarrow X^*_1 \longrightarrow X^*_2 \longrightarrow X^*_3 \longrightarrow X^*_4 \longrightarrow \ldots \longrightarrow \ldots\ldots\ X_n$$

Stable nuclide

- four natural decay series were established:

  - **^{232}Th → 208Pb (Thorium family)**
  - **^{235}AcU → 207Pb(Actinium family)**
  - **^{238}U → 206Pb(Uranium family)**
  - **^{241}Pu → 209Bi (Neptunium family**)

- Pu/Bi series was decayed in nature due to the relatively short half-life of ^{237}Np

V. Laws of radioactive disintegration:

The number of disintegrated nuclei per unit of time is proportional to the number of remaining nuclei (disintegrated name). We will limit our study to the simple case where :

$$X^* \longrightarrow X$$

	radiactive	stable
at t=0	N_0	0
at t	N_t	$N_0 - N_t$

• There is an equal probability for all nuclei of a radioactive element to decay.

• The rate of spontaneous disintegration of a radioactive element is proportional to the number of nuclei present at that time.

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$$\frac{dN}{dt} \propto \mathrm{N} \qquad (1)$$

N: number of atoms present at time t.

Removing proportionality sign, we get

$$\frac{dN}{dt} = -\lambda N \qquad (2)$$

λ: decay constant of the element.

Negative sign indicates that as t increases N decreases.

Rewriting Eq. (2) as

$$\frac{dN}{N} = -\lambda \mathrm{d}t \qquad (2.1)$$

Integrating both sides, we have $\int \frac{dN}{N} = -\lambda \int \mathrm{d}t$ (2.2)

$$\ln N = -\lambda t + c \qquad (2.3)$$

Where C is constant of integration and is evaluated by the fact that at t = 0 number of atoms of the radioactve element is N_0. Using this condition, we get :

$$C = \ln N_0$$

substituenting this value of C in eq. (2.3), we get :

$\ln N_t = -\lambda t + \ln N_0$ or $\ln\frac{Nt}{N0} = -\lambda t$ (2.4)

thus : $N_t = N_0\, e^{-\lambda t}$ or $N_0 = N_t\, e^{\lambda t}$ (2.5)

The exponential nature of this equation shows that it takes an infinite time for the whole of the radioactive material to disintegrate.

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V.1. Activity law (A):

$$A = - dN/dt = \lambda N$$

Substituting for N from Eq. (2.5)

$$N_t = N_0\, e^{-\lambda t} \qquad (2.5)$$

$$A = N_0\, \lambda\, e^{-\lambda t} \qquad (2.6)$$

Substituting $A_0 = \lambda N_0$

$$A = A_0\, e^{-\lambda t} \qquad (2.7) \quad \text{Activity Law}$$

A_0 is the activity at t = 0.

The exponential factor shows that the activity is decreasing in the same fashion as N.

Units of Radioactivity

The Becquerel (Bq): Disintegration per second, dps

dpmn : Disintegration per minute

dpyr : Disintegration per year

- The curie (Ci)

1 Ci = 37,000,000,000 Bq

$$\boxed{1Ci=3,7.10^{10}dps}$$

V.2. Half-life

Half-life is the time required for half of the atoms of a radioactive material to decay to another nuclear form.

At $t=T=t_{1/2}$; $N_t=\frac{N_0}{2}$ ($N_0/2$ unstable nuclei have disintegrated and N0/2 stable nuclei have formed)

$\text{Ln}\,\frac{N_0}{N_t} = \lambda t$ à $t=T= t_{1/2}$; $N_T=\frac{N_0}{2}$

$\Rightarrow \ln \frac{N_0}{\frac{N_0}{2}} = \lambda T \Rightarrow \ln 2 = \lambda T$

Et $\boxed{T=\frac{\ln 2}{\lambda}}$ ou $\boxed{\lambda=\frac{\ln 2}{T}}$

[λ] time $^{-1}$ (sec $^{-1}$, mn $^{-1}$, h^{-1} years $^{-1}$,……………t^{-1}).

General relationship $\boxed{\ln \frac{N_0}{N_t} = t.\frac{\ln 2}{T}}$

VI. Applications of radioactivity

VI.1. In medicine :

Medical Applications Radioisotopes with short half-lives are used in nuclear medicine because they have the same chemistry in the body as the nonradioactive atoms.

Radioisotopes have found extensive use in diagnosis and therapy, and this has given rise to a rapidly growing field called nuclear medicine. These radioactive isotopes have proven particularly effective as tracers in certain diagnostic procedures.

Though many radioisotopes are used as tracers, iodine-131, phosphorus-32, and technetium-99*m* are among the most important.

- Physicians employ iodine-131 to determine cardiac output, plasma volume, and fat metabolism and particularly to measure the activity of the thyroid gland where this isotope accumulates.
- Phosphorus-32 is useful in the identification of malignant tumours because cancerous cells tend to accumulate phosphates more than normal cells do.
- Technetium-99*m*, used with radiographic scanning devices, is valuable for studying the anatomic structure of organs.
- Such radioisotopes as cobalt-60 and cesium-137 are widely used to treat cancer. They can be administered selectively to malignant tumours and so minimize damage to adjacent healthy tissue.

• In the organs of the body, they give off radiation that exposes a scan giving an image of an organ.

VI.2. In industry

- **nuclear fission**

In nuclear fission the nucleus of an atom breaks up into two lighter nuclei. The process may take place spontaneously in some cases or may be induced by the excitation of the nucleus with a variety of particles (e.g., neutrons, protons, deuterons, or alpha particles) or with electromagnetic radiation in the form of gamma rays. In the fission process, a large quantity of energy is released, radioactive products are formed, and several neutrons are emitted.

An important example of nuclear fission is the splitting of the uranium-235 nucleus when it is bombarded with neutrons. Various products can be formed from this nuclear reaction, as described in the equations below.

- $^{235}U + {}^{1}n \rightarrow {}^{141}Ba + {}^{92}Kr + 3\,{}^{1}n$
- $^{235}U + {}^{1}n \rightarrow {}^{144}Xe + {}^{90}Sr + 2\,{}^{1}n$
- $^{235}U + {}^{1}n \rightarrow {}^{146}La + {}^{87}Br + 3\,{}^{1}n$
- $^{235}U + {}^{1}n \rightarrow {}^{137}Te + {}^{97}Zr + 2\,{}^{1}n$
- $^{235}U + {}^{1}n \rightarrow {}^{137}Cs + {}^{96}Rb + 3\,{}^{1}n$

These neutrons can induce fission in a near by nucleus of fissionable material and release more neutrons that can repeat the sequence, causing a chain reaction in which a large number of nuclei undergo fission and an enormous amount of energy is released.

If controlled in a nuclear reactor, such a chain reaction can provide power for society's benefit. If uncontrolled, as in the case of the so-called atomic bomb, it can lead to an explosion of awesome destructive force.

- **Nuclear Fusion**

In nuclear fusion reactions, at least two atomic nuclei combine/fuse into a single nucleus. Subatomic particles such as neutrons or protons are also formed as products in these nuclear reactions.

An illustration of the nuclear fusion reaction between deuterium (^{2}H) and tritium (^{3}H) that yields helium (^{4}He) and a neutron (^{1}n) is provided above. Such fusion reactions occur at the core of the sun and other stars. The fusion of deuterium and tritium nuclei is accompanied by a loss of approximately 0.0188 amu of mass (which is completely converted into energy). Approximately $1.69*10^{9}$ kilojoules of energy are generated for every mole of helium formed.

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

VI.3. In science

Research in the Earth sciences has benefited greatly from the use of radiometric-dating techniques, which are based on the principle that a particular radioisotope (radioactive parent) in geologic material decays at a constant known rate to daughter isotopes. Using such techniques, investigators have been able to determine the ages of various rocks and rock formations and thereby quantify the geologic time scale (*see* geochronology: Absolute dating). A special application of this type of radioactivity age method, carbon-14 dating, has proved especially useful to physical anthropologists and archaeologists. It has helped them to better determine the chronological sequence of past events by enabling them to date more accurately fossils and artifacts from 500 to 50,000 years old.

Radioisotopic tracers are employed in :

Environmental studies, as, for instance, those of water pollution in rivers and lakes and of air pollution by smokestack effluents.

They also have been used to measure deep-water currents in oceans and snow-water content in watersheds. Researchers in the biological sciences, too, have made use of radioactive tracers to study complex processes. For example, thousands of plant metabolic studies have been conducted on amino acids and compounds of sulfur, phosphorus, and nitrogen.

Other applications include the use of radioisotopes to measure (and control) the thickness or density of metal and plastic sheets, to stimulate the cross-linking of polymers, to induce mutations in plants in order to develop hardier species, and to preserve certain kinds of foods by killing microorganisms that cause spoilage. In tracer applications radioactive isotopes are employed, for example, to measure the effectiveness of motor oils on the wearability of alloys for piston rings and cylinder walls in automobile engines.