Regina Pinto de Carvalho

APPLICATIONS OF NUCLEAR ENERGY

INDUSTRY • ENVIRONMENT
FOOD PRODUCTION • CULTURAL HERITAGE

IAEA
International Atomic Energy Agency
Atoms for Peace

Regina Pinto de Carvalho

APPLICATIONS OF NUCLEAR ENERGY

Industry • Environment
Food production • Cultural heritage

IAEA
International Atomic Energy Agency
Atoms for Peace

Published by
International Atomic Energy Agency - IAEA
Vienna International Centre
PO Box 100 / 1400 Vienna, Austria
www.iaea.org

Technical revision

Ana Márcia Greco de Sousa

Illustration

Henrique Cupertino

Lay-out

Christiane Morais

Translation

Custom Solutions Ltda.

Support
International Atomic Energy Agency - IAEA
Sociedade Brasileira de Física – SBF
Comissão Nacional de Energia Nuclear – CNEN
Sociedade Brasileira para o Progresso da Ciência - SBPC

In general, people are mostly unaware of the peaceful applications of nuclear energy. Lending continuity to the project initiated in our previous book, "Applications of Nuclear Energy in Health", the objective of this second book is to provide information and examples of the use of nuclear energy in areas as diverse as industry, environmental studies, food production and preservation of cultural assets. We thus hope to provide high school teachers with useful bibliography on the subject, at an appropriate level, to complement classroom activities.

A brief introduction outlines the fundamentals of Nuclear Physics, followed by chapters on applications in various areas. These stand-alone chapters can be read in any order. To allow this, we have chosen to repeat, in some chapters, information we deem essential, in order to assure its understanding.

The illustrations are presented so they can be understood by colorblind people. If you, dear reader, have this characteristic and find it difficult to interpret some figures, please contact us so that we can make the necessary improvements.

We would like to thank the many experts from all over the world who have dedicated time to talking to us and/or reading the material, sending information and references. To the extent possible, they are mentioned at the end of each chapter.

In particular, we thank Prof. João Alberto Osso Júnior (IAEA) for his comments and observations. We also thank him for handling the operational part of the Project.

We thank Dr. Raul Ramirez (IAEA) for supporting the Project.

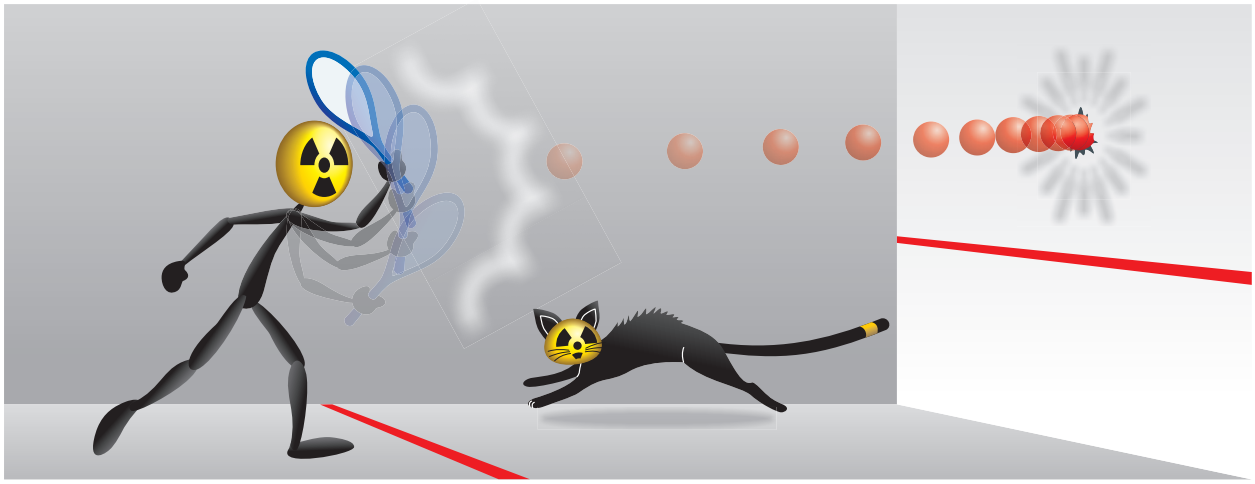
In addition, we wish to express our deepest appreciation to Prof. Aldo Malavasi (IAEA), who embraced the project and allowed it to grow much beyond what we had initially imagined.

Regina
January/2019

(...) and we shouldn´t forget that the structure of the atom cannot be seen with our eyes but we know it´s there. I know about many things that I have not [actually] seen. As have you...

Clarice Lispector - translated from *A Hora da Estrela*

CHAPTER I - FUNDAMENTALS



We can describe an **atom** as having a positive **nucleus** and negative **electrons**, located in a region around the nucleus. The volume of the atom is determined by the so-called "electronic cloud" and its mass is mainly related to the mass of the nucleus. The transformations of nuclei through bombardment and emissions are the object of the study of Nuclear Physics.

This chapter presents a summary of the fundamentals of Nuclear Physics that will be necessary for the understanding of later chapters.[1]

Composition of the nucleus

The particles that make up the nucleus are called **nucleons**. They may be positive (the **protons**) or have no electric charge (the **neutrons**). There are forces of attraction between the nucleons, which need to compensate for the electric repulsion forces between the protons, so that the nucleus remains cohesive.

The chemical elements are distinguished from each other by the number of protons in their nuclei (equal to the number of electrons, if the atom is neutral). They may have different numbers of neutrons, maintaining the same chemical properties, but having different masses. Atoms of the same element with different numbers of neutrons are called **isotopes**. Most elements have natural isotopes. Many natural isotopes are stable; others, unstable, decay by undergoing radioactive emissions.

The nuclei are represented by the symbol of the element to which they correspond; a subscript on the lower left of the symbol represents its atomic number (number of protons), and a superscript on the upper left of the symbol represents its mass number (number of protons + number of neutrons). If a nucleus is in an excited state, this is specified by an asterisk to the right of the symbol. The example below shows the representation of a uranium-236 nucleus (92 protons, 144 neutrons) in an excited state:

$$^{236}_{92}U^{*} \qquad \text{i-1}$$

[1] For a more detailed development of the subject, the reader can turn to the first chapters of the previous book: "Applications of Nuclear Energy in Health" (R P de Carvalho and SM Velasques de Oliveira), SBPC-IAEA (2017), available at: <http://portal.sbpcnet.org.br/livro/applicationsofnuclearenergyinhealth.pdf>. Accessed Jan 2019.

It is not necessary to write the number of protons, since that is determined by the symbol of the element; however, it may be useful to display this number to facilitate the visualization of nuclear processes.

Nuclear reactions

A nucleus can be modified by spontaneous emission, absorption or bombardment of particles, photons or other nuclei.

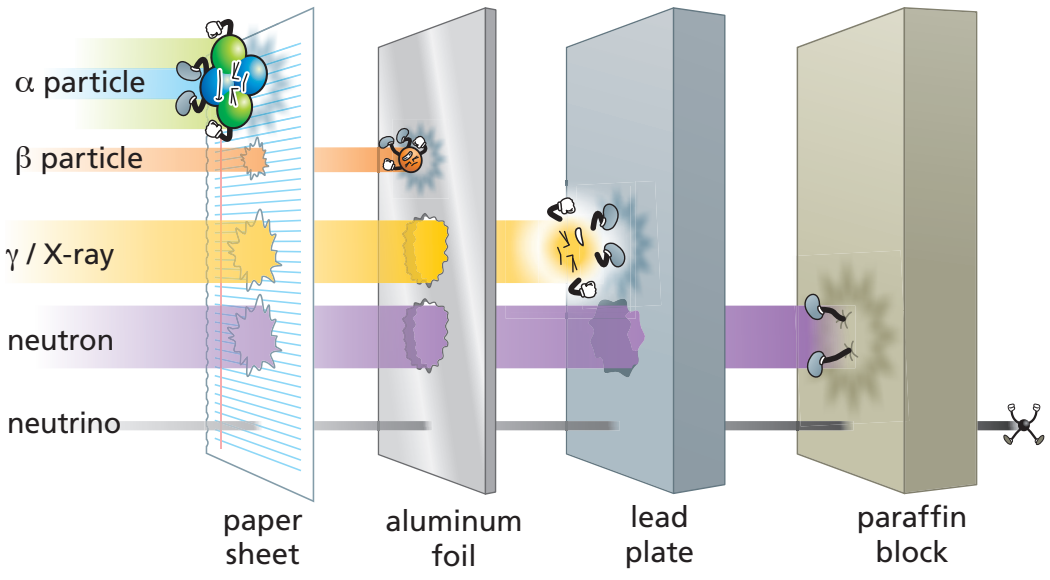
When a nucleus is not in equilibrium, it can **decay**, emitting particles or radiation, to achieve a more stable configuration. Isotopes that decay spontaneously are called **radioisotopes**. Nuclear emissions are described in Table I-1 and Figure I-1.

Table I-1 - Characteristics of nuclear emissions

Particle	Composition	Shielded or Blocked by
α	2 protons + 2 neutrons	sheet of paper
β^-	electron	aluminum foil
β^+	positron (similar to an electron but with positive charge)	aluminum foil
ν	neutrino	- -
$\bar{\nu}$	anti-neutrino	- -
γ	high energy photon	lead plate or some meters of concrete
n	neutron	block of boron or paraffin

Based on: R. P. de Carvalho and S. M. Velasques de Oliveira - Applications of Nuclear Energy in Health - IAEA, SBPC, 2017 - Available at: <http://portal.sbpcnet.org.br/livro/applicationsofnuclearenergyinhealth.pdf>. Accessed Jan 2019.
Remarks: Protons and neutrons exist permanently inside the nucleus; β particles are created during the emission process, in which there is always the emission of neutrinos. These are uncharged particles, of mass much smaller than that of the electron, and which have momentum and energy, to account for the conservation of these quantities during the nuclear transformations. Because they are neutral and have very small mass, neutrinos rarely interact with matter.

Figure I-1: Materials that can shield nuclear emissions



Based on: R. P. de Carvalho and S. M. Velasques de Oliveira - Applications of Nuclear Energy in Health - IAEA, SBPC, 2017 – Available at: <http://portal.sbpcnet.org.br/livro/applicationsofnuclearenergyinhealth.pdf>. Acessed Jan 2019.

Nuclear emissions have high energies and are able to ionize the atoms with wich they colide (to ionize = to strip electrons away). Therefore, they are called **ionizing radiation**. X-rays, although they do not have a nuclear origin, have enough energy to ionize matter, and are therefore also considered as ionizing radiation.

Nuclear reactions can be represented in a manner similar to chemical reactions. The following are examples of nuclear reactions:

$$^{238}_{94}\mathrm{Pu} \rightarrow {}^{234}_{92}\mathrm{U} + {}^{4}_{2}\alpha \qquad \text{(i-2)}$$

$$^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow ({}^{236}_{92}\mathrm{U}^{*}) \rightarrow {}^{141}_{56}\mathrm{Ba} + {}^{92}_{36}\mathrm{Kr} + 3{}^{1}_{0}\mathrm{n} + \mathrm{E} \qquad \text{(i-3)}$$

$$^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} + \mathrm{E} \qquad \text{(i-4)}$$

$$^{18}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{p} \rightarrow {}^{18}_{9}\mathrm{F} + {}^{1}_{0}\mathrm{n} + \mathrm{E} \qquad \text{(i-5)}$$

$$^{18}\mathrm{O}\ (\mathrm{p,n})\ ^{18}\mathrm{F} \qquad \text{(i-6)}$$

$$^{7}_{4}\mathrm{Be} + {}^{0}_{-1}\mathrm{e}^{-} \rightarrow {}^{7}_{3}\mathrm{Li} + \nu + \gamma \qquad \text{(i-7)}$$

Equation i-2 describes the **spontaneous decay** of plutonium-238 which, after the emission of an α particle, is transformed into uranium-234.

In equation i-3, a uranium-235 nucleus absorbs a neutron and transforms into uranium-236, in an excited state; then it divides into two smaller nuclei, barium-141 and krypton-92, emitting 3 neutrons. This reaction is called **fission** and releases a large amount of energy.

Equation i-4 describes the reaction between a hydrogen isotope with 1 proton and 1 neutron (the **deuterium**, which can also be represented by the symbol D) and another isotope of hydrogen, with 1 proton and 2 neutrons (**tritium**, also represented by T). The two nuclei fuse into a nucleus of helium-4, emitting 1 neutron and great amount of energy. This reaction is called **fusion** and is one of the main sources of energy of the Sun and the stars.

Equation i-5 describes the **bombardment** of oxygen-18 by a proton, resulting in fluorine-18, while emitting a neutron and energy.

Equation i-6 is a simplified way of describing the reaction of equation i-5: the initial nucleus, the involved particles (in parentheses) and the final nucleus are indicated.

In equation i-7, we have an example of **electron capture**: the beryllium-7 nucleus absorbs an electron from its own electron cloud, transforming itself into lithium-7 and emitting a neutrino and energy in the form of γ radiation.

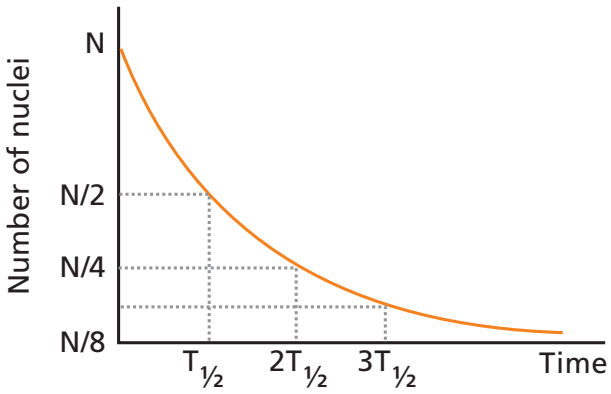
Radioactive decay

During radioactive decay, the number N of radioisotopes decreases with time t, from an initial number N_0, according to an exponential law:

$$N = N_0 e^{-\lambda t} \qquad \text{i-8}$$

The time required for the decay of half the nuclei in a sample is called the half-life and represented by the symbol $T_{1/2}$. Thus, if at the beginning of an observation there are N radioactive nuclei in the sample, after a half-life there will remain only $\frac{N}{2}$ radioactive nuclei; after 2 half-lives, there will be only $\frac{1}{2} \cdot \frac{N}{2} = \frac{N}{4}$ radioactive nuclei, and so on. Figure I-2 shows the variation of the number of radioactive nuclei as a function of time.

Figure I-2: Variation of the number of radioactive nuclei as a function of time, in a case of spontaneous decay



Source: R. P. de Carvalho and S. M. Velasques de Oliveira - Applications of Nuclear Energy in Health - IAEA, SBPC, 2017 - Available at: <http://portal.sbpcnet.org.br/livro/applicationsofnuclearenergyinhealth.pdf>. Acessed Jan 2019.

Obtaining radioelements

Naturally occurring radioelements are those whose half-life is greater than or comparable to the Earth's age, since the others have decayed into stable nuclei. We also find natural radioelements with a shorter half-life that belong to the decaying chain of long half-life elements. As an example, radium-228 ($T_{½}$ = 5.8 years) can be found in Nature, since it derives from the decay of thorium-232 ($T_{½}$=14 · 10^9 years). There are also radioelements with half-lives shorter than the Earth's age created through the bombardment by cosmic rays of the molecules present in the upper atmosphere..

Other radioisotopes may be artificially obtained by bombardment with charged particles or neutrons. Many are also formed in man-made fission reactions; when this occurs in nuclear reactors, fission products can be reused for other uses. Tests and nuclear explosions that occurred in the last century have released radioelements in the Earth's atmosphere, and those with longer half-lives are still present throughout the planet.

When the radioisotopes present in the atmosphere, whether of natural or anthropogenic origin, fall on the ground, they are called FRNs (Fallout RadioNuclides).

Table I-2 shows some radioelements, their origin and half-life values.

Table I-2 - Origin and half-life of some radioelements

Radioelement	Half-life	Origin
^{232}Th	14 · 10^9 years	Half-life comparable to that of Earth's age
^{238}U	4.5 · 10^9 years	
^{40}K	1.3 · 10^9 years	
^{14}C	5,730 years	Formed in the upper atmosphere
^{3}H	12.3 years	
^{7}Be	53 days	

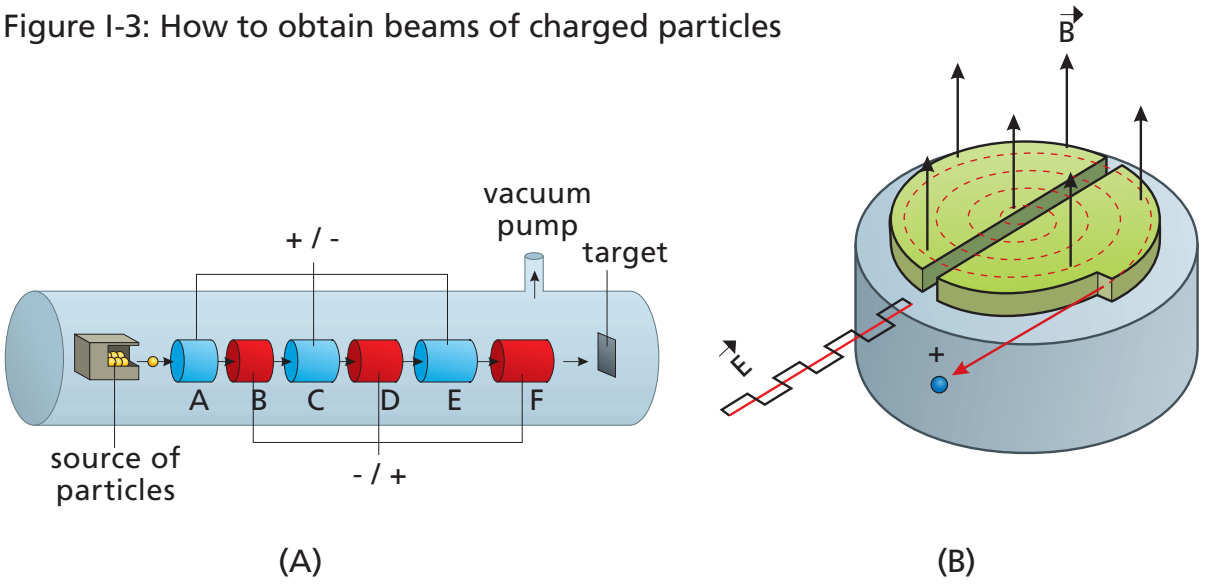
Radioelement	Half-life	Origin
^{210}Pb	22.2 years	product of ^{238}U decay
^{239}Pu	$24 \cdot 10^3$ years	Formed in nuclear tests and explosions
^{137}Cs	30 years	
^{90}Sr	28 years	
^{60}Co	5.3 years	Obtained in reactors for medical and industrial applications
^{131}I	12 days	

Obtaining ionizing radiation beams

In order to promote nuclear reactions and obtain radioisotopes artificially, it is necessary to obtain beams of particles or radiation.

Beams of charged particles are obtained in linear accelerators or cyclotrons, as shown in Figure I-3.

Figure I-3: How to obtain beams of charged particles



A: In a linear accelerator, a metal filament is heated to separate electrons from the metal atoms; these electrons are accelerated in regions with alternating electric fields, synchronized with the movement of the electrons, in order to accelerate them always in the same direction. Proton beams can be obtained in a similar way. The beams are concentrated using magnetic fields. B: In a cyclotron, at the same time as they are accelerated, the charged particles are deflected by magnetic fields, moving in a spiral path. At each turn, the electric and magnetic field values are adjusted to increase beam energy. Source: R. P. de Carvalho and S. M. Velasques de Oliveira - Applications of Nuclear Energy in Health - IAEA, SBPC, 2017. Available at: <http://portal.sbpcnet.org.br/livro/applicationsofnuclearenergyinhealth.pdf>. Acessed Jan 2019.

The neutron beams are obtained inside fission reactors, which produce high energy neutrons. They are moderated (i.e. have their kinetic energy reduced) by hydrogen-rich material contained in the reactor, usually water or heavy water (containing heavy isotopes of hydrogen). The collisions of neutrons with nuclei of similar mass (hydrogen or deuterium) cause the energy to be distributed among them. Another way to obtain neutrons is to use indirect reactions, in which charged particles are directed to a target and promote a reaction, thus emitting the desired neutrons. There are also some radioisotopes that decay with neutron emission.

X-rays can be obtained by deceleration of charged particles or by bombardment. When charged particles are decelerated, there is an emission of X-rays, in the phenomenon known as *Bremsstrahlung*, a German word for braking radiation. This effect is obtained by directing the particles against a target. At the same time, the particles displace electrons from the innermost layers of the target atoms; higher-level electrons "fall" to take the place of released electrons, and thereby emit X-rays whose energy corresponds to the energy difference between the initial and the final electron states.

Interaction of radiation with matter

The interaction of radiation with matter depends on the type of radiation: whether from photons (electromagnetic radiation), charged particles or neutrons.

The electromagnetic radiation (photons) interacts with matter in three different ways, depending on its energy: the photoelectric effect, the Compton effect and pair production (Figure I-4).

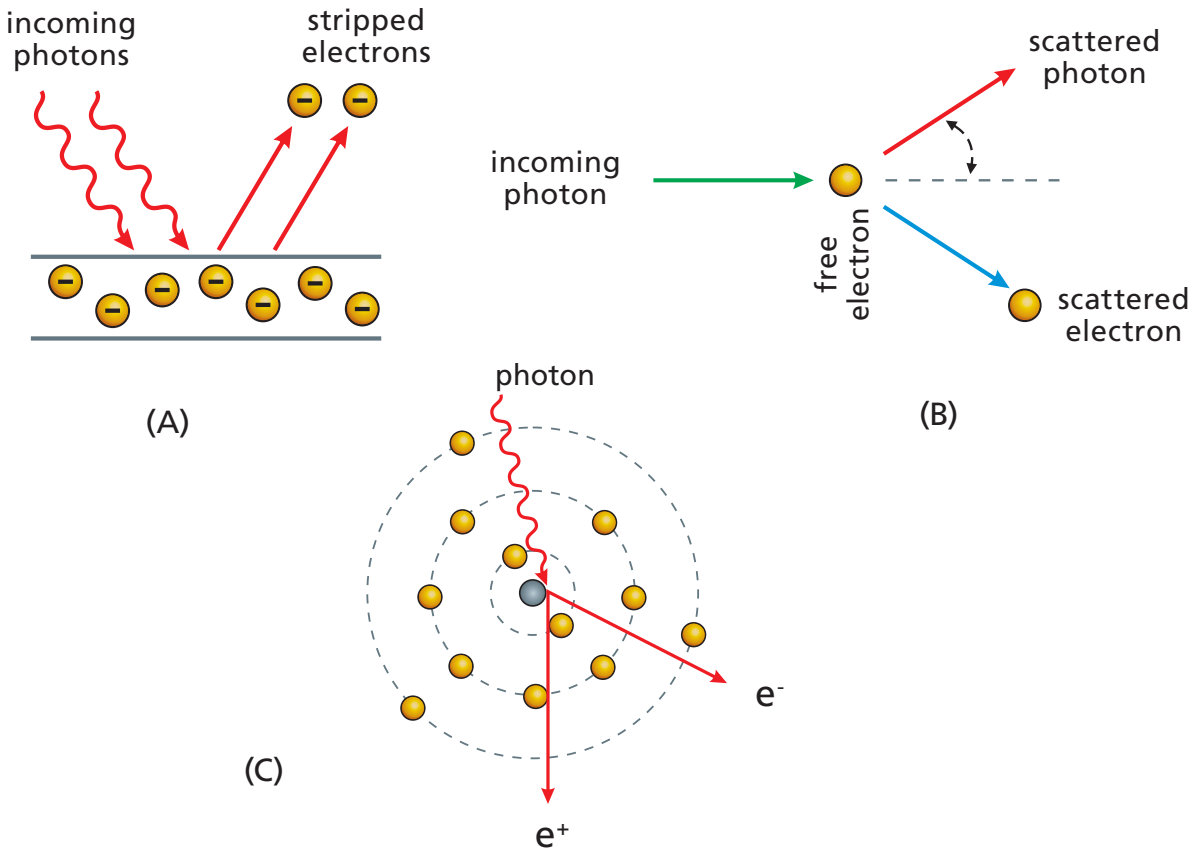
In the **photoelectric effect**, a photon strikes a metal surface and releases an electron from the surface. This phenomenon occurs for lower photon energies.

With intermediate photon energy values, a photon and an electron free or weakly bound to an atom behave like two colliding particles, their trajectories being modified according to the laws of conservation of energy and momentum. This phenomenon is called the **Compton effect**.

If the energy of the photon is very high, **pair production** can occur: the photon disappears, giving rise to an electron and a positron, obeying the law of conservation of mass-energy. This phenomenon occurs in the vicinity of a nucleus, which recoils, obeying the law of conservation of momentum.

The inverse phenomenon may also occur, **pair annihilation**: a positron and an electron mutually annihilate each other, generating photons of energy corresponding to the masses and energies of the pair. Although they are not of nuclear origin, these photons are called γ- radiation due to their high energy.

Figure I-4: A: illustration of the photoelectric effect, B: Compton effect and C: pair formation



Source: R. P. de Carvalho and S. M. Velasques de Oliveira - Applications of Nuclear Energy in Health - IAEA, SBPC, 2017 - Available at: <http://portal.sbpcnet.org.br/livro/applicationsofnuclearenergyinhealth.pdf>. Acessed Jan 2019.

The charged particles interact with atoms mainly by releasing electrons (ionization) or by transferring them to higher energy levels (excitation). During the interaction, they decelerate and emit electromagnetic radiation.

Neutrons, as they have no electrical charge, interact with the nuclei through scattering (collisions with energy exchange) or capture, in which case they take the nucleus to an excited state and provoke nuclear reactions or fission of the nucleus.

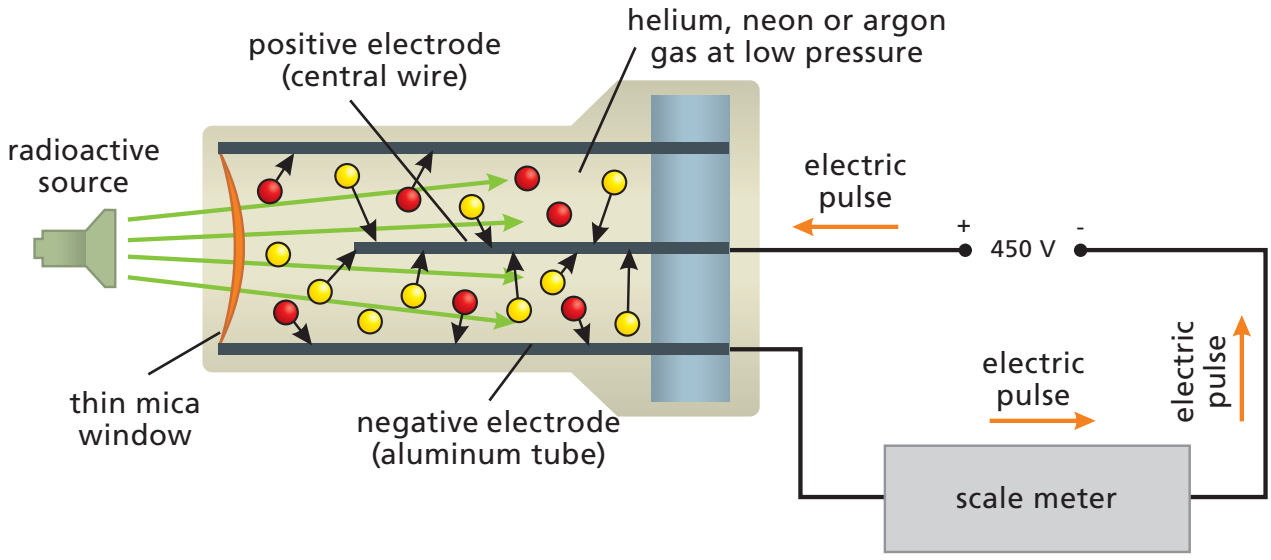
Detection of ionizing radiation

The development of detectors for each type of radiation is based on the ways it interacts with matter. Generally, a radiation detector consists of a radiation-sensitive element or material and a system that transforms the effects of radiation into a measurable quantity related to the amount of radiation. Frequently, the radiation energy is transformed into an electric quantity, which can be easily and accurately interpreted or measured.

The first radiation detectors used films with **photographic emulsion**. The emulsion consists of grains of silver salts, which are ionized by the passage of the radiation. The silver is reduced to metallic silver, forming an image that shows the radiation path. Photographic emulsions are still used in special cases.

Currently, the most common detectors contain gas, which is ionized by the incoming radiation; the ions move through an electric potential, causing an electrical pulse that can be measured. The best-known gas detector is the **Geiger-Müller** counter (Figure I-5).

Figure I-5: Schematic of a Geiger-Müller counter

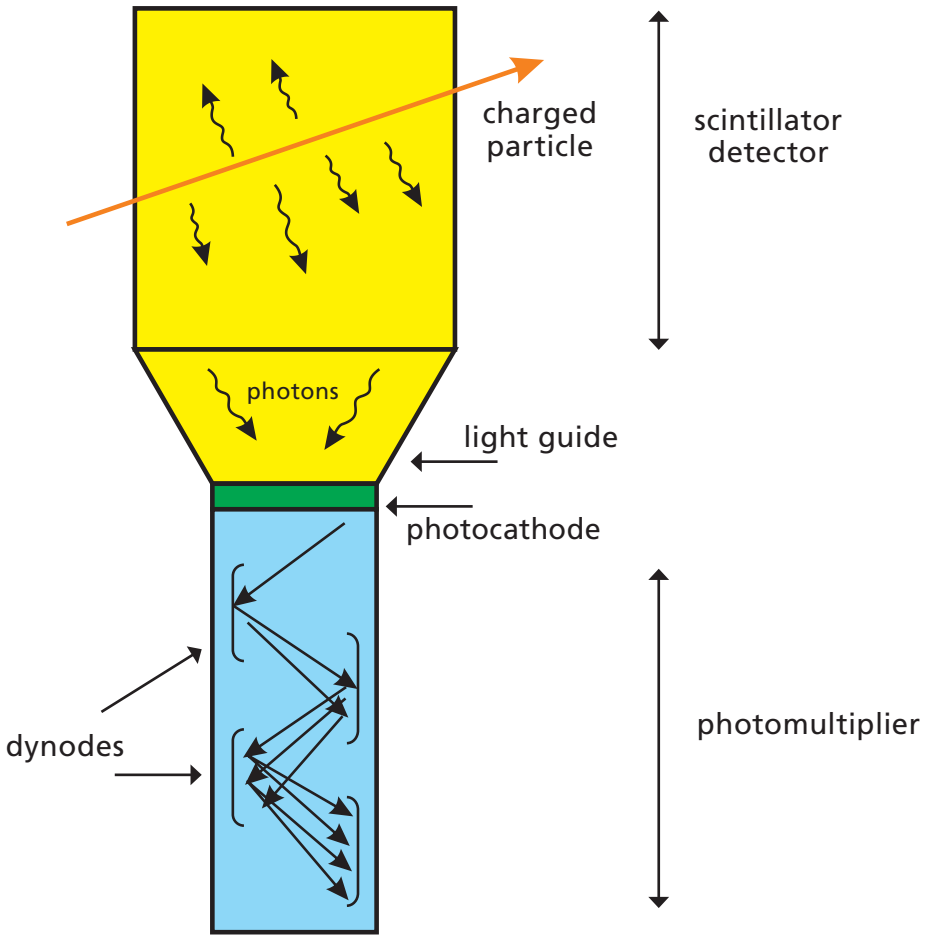


The radiation ionizes the gas contained in a chamber; the ions move through an electrical potential between the shell and a central wire, causing an electrical pulse to be recorded in an external meter.

Based on: R. P. de Carvalho and S. M. Velasques de Oliveira - Applications of Nuclear Energy in Health - IAEA, SBPC, 2017 - Available at: <http://portal.sbpcnet.org.br/livro/applicationsofnuclearenergyinhealth.pdf>. Acessed Jan 2019.

More modern detectors use **scintillators**, which are crystals that emit light after the ionization caused by the passage of radiation; the emitted photons generate electrons, which are multiplied and measured in an external circuit (Figure I-6).

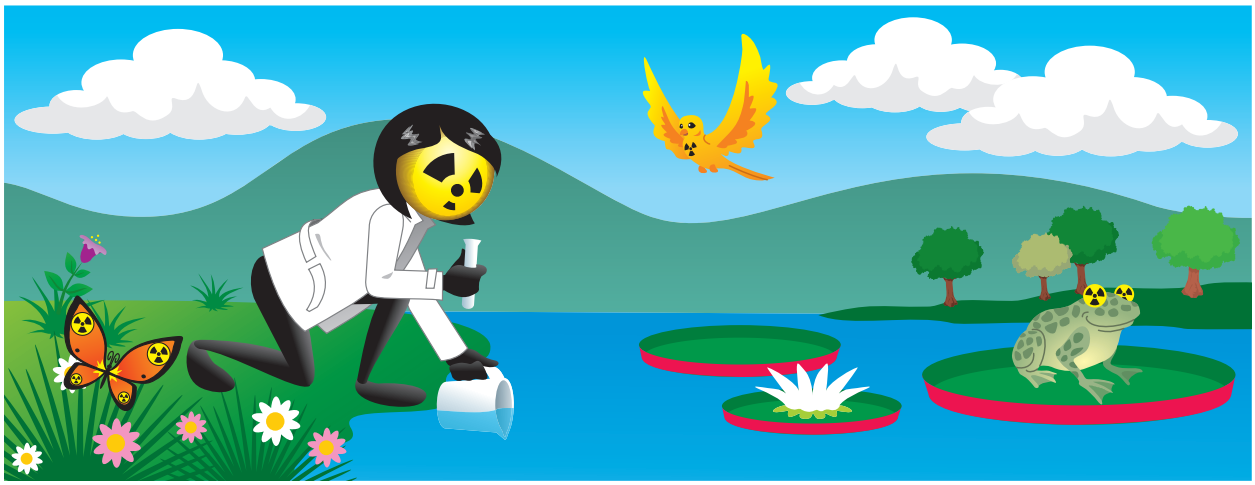
Figure I-6: Schematic of a scintillator detector



The scintillating crystal emits photons after the ionization caused by the passage of radiation; when the photons attain the photocathode, electrons are released due to the photoelectric effect. The electrons emitted are accelerated and collide against metal plates (dynodes), from which other electrons are released. The amplified electron beam forms an electric pulse, which is analyzed by an external circuit.
Source: R. P. de Carvalho and S. M. Velasques de Oliveira - Applications of Nuclear Energy in Health - IAEA, SBPC, 2017 - Available at: <http://portal.sbpcnet.org.br/livro/applicationsofnuclearenergyinhealth.pdf>. Acessed Jan 2019.

It is also possible to perform radiation detection by using **semiconductor materials**: the radiation ionizes a semiconductor crystal and the emitted electrons are trapped at unoccupied levels of energy, in impurities of the crystal. These electrons can be released, for example, by increasing the temperature of the crystal; upon returning to their original energy levels, they emit photons, which can be transformed into electrical pulses.

CHAPTER II - STABLE ISOTOPES



Almost all the elements have several isotopes (nuclei with the same number of protons, but different number of neutrons), occurring in nature in different proportions. Some are stable, others emit radiation of well-defined type, energy and half-life. As we shall see below, it is possible to use the ratio of heavy to light isotopes to determine certain characteristics of the substances and compounds formed by these elements.

Water isotopes

The water molecules (H_2O) are mainly formed by ${}^{1}_{1}H$ and ${}^{16}_{8}O$, but there is a small number of molecules formed by ${}^{2}_{1}H$ (deuterium), ${}^{17}_{8}O$ or ${}^{18}_{8}O$. Table II-1 shows the average abundance of stable isotopes of hydrogen and oxygen. The determination of these average values is done using sea water.

Table II-1 - Abundance of stable isotopes in sea water

Hydrogen isotope	Relative abundance
${}^{1}_{1}H$	0.99985
${}^{2}_{1}H$	0.00015

Oxygen isotope	Relative abundance
${}^{16}_{8}O$	0.99757
${}^{17}_{8}O$	0.00038
${}^{18}_{8}O$	0.00205

The standard values for the relative abundances of hydrogen and oxygen in seawater are measured at the International Atomic Energy Agency (IAEA) labs in Vienna, Austria, using a mixture of water from five continents, and are known by the acronym VSMOW (from Vienna Standard Mean Ocean Water).

The variation in the relative abundance of stable isotopes δ in a given sample is related to the ratio in the standard sample by:

$$\delta = \frac{(R_{sample} - R_{std})}{R_{std}} \cdot 1000 \text{ ,}$$

where $R = \frac{[\text{heavy isotope concentration}]}{[\text{light isotope concentration}]}$.

The units of δ are ‰ (*permil*).[2] For example, if we have a sample, with $\delta\,^{18}O = -10‰$, this indicates that:

$$\frac{(R_{sample} - R_{std})}{R_{std}} \cdot 1000 = -10$$

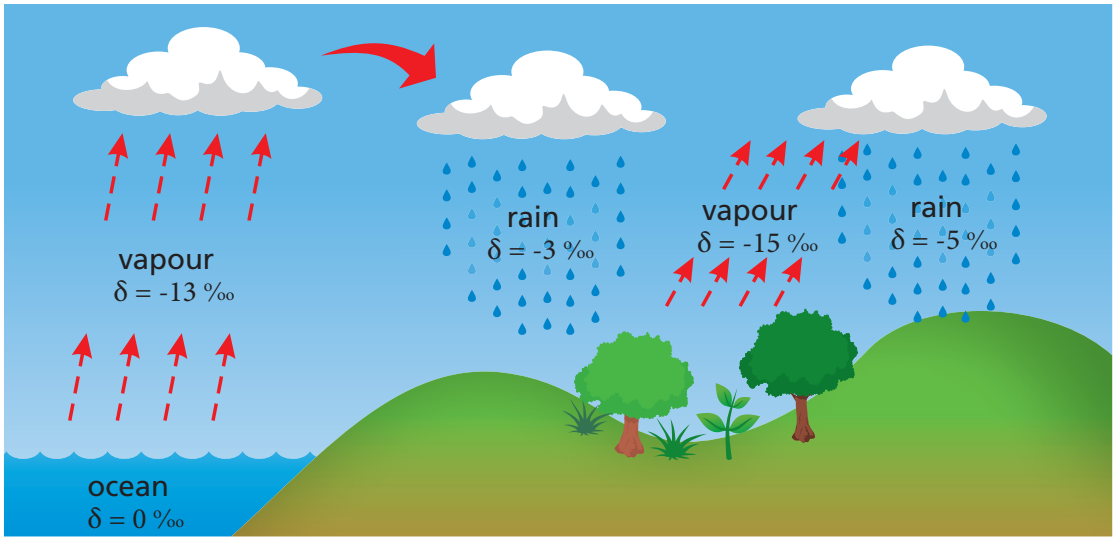
$$R_{sample} = 0{,}99 R_{std}$$

that is, the ratio of $\frac{[^{18}O]}{[^{16}O]}$ in the sample is 1% less than in the standard.

It has been observed that molecules containing lighter isotopes are more likely to evaporate or participate in chemical reactions, because molecular bonds are more easily broken. For the same reason, molecules with heavier isotopes are more likely to remain in condensed phases.

From these observations, it is possible to study the evolution of δ in the path described by water from evaporation in the oceans to the formation of rivers and lakes by rainfall. Figure II-1 gives an example of this path. The change in the isotopic distribution during a vaporization/condensation cycle is called **Rayleigh fractionation**.

Figure II-1: The variation of $\delta\,^{18}O$ in the water cycle



The standard is given by the isotopic composition of sea water, $\delta = 0\ ‰$. The evaporation is easier for the lighter isotope: $\delta_1(\text{vapour}) = -13\ ‰$. The clouds move to the mainland, where the vapor condenses in rainfall and the inverse occurs: $\delta_1(\text{rain}) = -3\ ‰$. Then the water evaporates again, with $\delta_2(\text{vapour}) = -15\ ‰$ and the clouds are carried by the wind from the coast to the inland regions, where they condense giving $\delta_2(\text{rain}) = -5\ ‰$.

Stable isotopes in organic material

The study of the origin or transport of organic matter can be done using the isotopic ratios of carbon, nitrogen or sulfur, in addition to the hydrogen and oxygen ratios shown above. Table II-2 shows the relative abundance of the major stable isotopes of these three elements.

[2] The use of *permil* (a.k.a. parts per thousand) is a way of expressing ratios in terms of whole numbers. Given a ratio or fraction, it is converted to a permil-age by multiplying by 1000 and appending a "mil sign" ‰. From: <http://mathworld.wolfram.com/Permil.html>. Accessed Jan 2019.

Table II-2 - Relative abundance of carbon, nitrogen and sulfur isotopes

Carbon isotope	Relative abundance	Nitrogen isotope	Relative abundance	Sulfur isotope	Relative abundance
$^{12}_{6}C$	0.9893	$^{14}_{7}N$	0.99636	$^{32}_{16}S$	0.9502
$^{13}_{6}C$	0.0107	$^{15}_{7}N$	0.00364	$^{34}_{16}S$	0.0421

The reference values for the relative abundances of the isotopes are measured by the IAEA laboratory in Vienna, which provides the standard samples. The standard for carbon is measured in Belemnite, limestone from marine fossils from the Pee Dee geological formation in North Carolina (USA), and is named VPDB (Vienna-Pee Dee Belemnite); the standard for nitrogen is established using atmospheric air and bears the name AIR; for sulfur, the VCDT (Vienna-Canyon Diablo Troilite) standard, measured in meteorites found in the Canyon Diablo region (USA) is used.[3]

Measurement of isotopic variations

Tables II-1 and II-2 show that, for many elements, the ratio between the natural concentrations of the different isotopes has orders of magnitude of 10^{-3} or even less. Therefore, the measuring instruments must have high sensitivity and precision. **Mass Spectrometers** or **Infrared Absorption Spectrometer**s are currently used.

Mass Spectrometer

Figure II-2 shows the operating scheme of a Mass Spectrometer (MS), which is an equipment used to measure the number of atoms with a given mass.

The sample to be analyzed is vaporized and ionized, and the ions are accelerated by an electric field, acquiring a velocity $\overrightarrow{v_0}$. In the figure, the ion shown is negative and its velocity is horizontal, pointing to the right.

The ion beam then passes through a velocity filter, where there is an electric field $\vec{E}$ and a magnetic field $\vec{B}$. In the figure, $\vec{E}$ is vertical, from top to bottom, and $\vec{B}$ is perpendicular to the page and penetrates it.

In this region, each negative ion is subjected to an electric force $\overrightarrow{F_E}$, vertical upwards, and to a magnetic force $\overrightarrow{F_B}$, vertical downwards. The electric force is proportional to the charge q of the ion, that is, $F_E = qE$, and the magnetic force is proportional to the charge and velocity v of the ion, that is $F_B = qvB$. Therefore, it is possible to choose the field intensities so that the electric and magnetic forces cancel out for ions with a chosen speed; these ions will travel in a straight line and reach an opening at the end of that region.

After crossing the velocity filter, the ions reach a region where there is only a magnetic field, perpendicular to the direction of its velocity. This field modifies the displacement of the ionic beam, causing the ions to travel a circular path whose radius depends on the mass of the ions. This can be deduced if we observe that the magnetic force is the centripetal force that causes the circular movement of each ion:

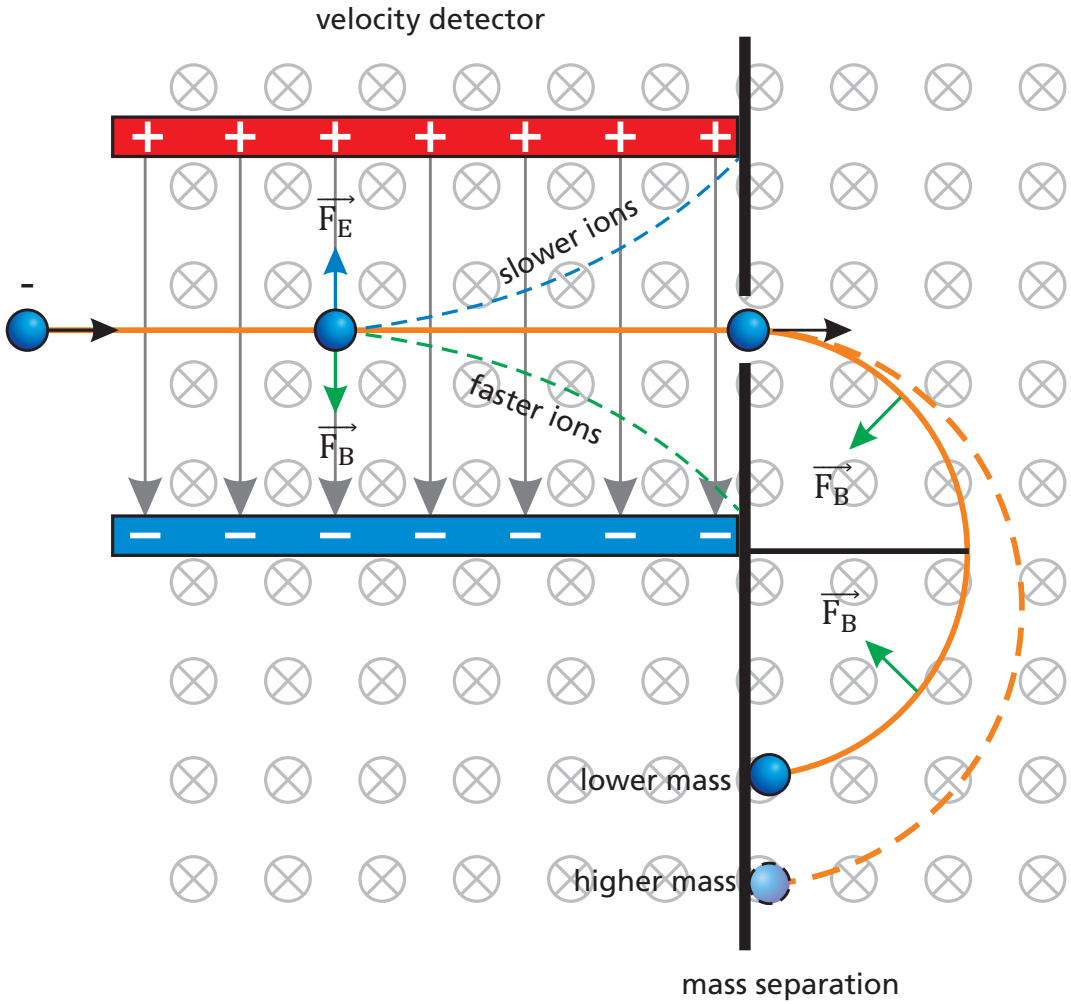
$$\frac{mv^2}{R} = qvB$$

$$R = m \cdot \frac{v}{qB}$$

[3] Standards for isotopic ratios may also be provided by other international organizations, for example, by the NIST (National Institute of Standards and Technology, USA) or IRMM (Institute for Reference Materials and Measurements, European Community).

A detector plate, placed at the end of the path of the ions, measures the beam intensity for each value of the radius, that is, for each mass value.

Figure II-2: Scheme of a mass spectrometer



The mass spectrometer has the drawback of being a large piece of equipment and requiring shielding to prevent external magnetic fields from interfering in the measurement. In addition, if different ions with the same charge/mass ratio are present, they will also be detected. The advantage of this technique is that the same equipment can be used to measure isotopic ratios in different elements; it is mainly used for H, C, O, N or S.

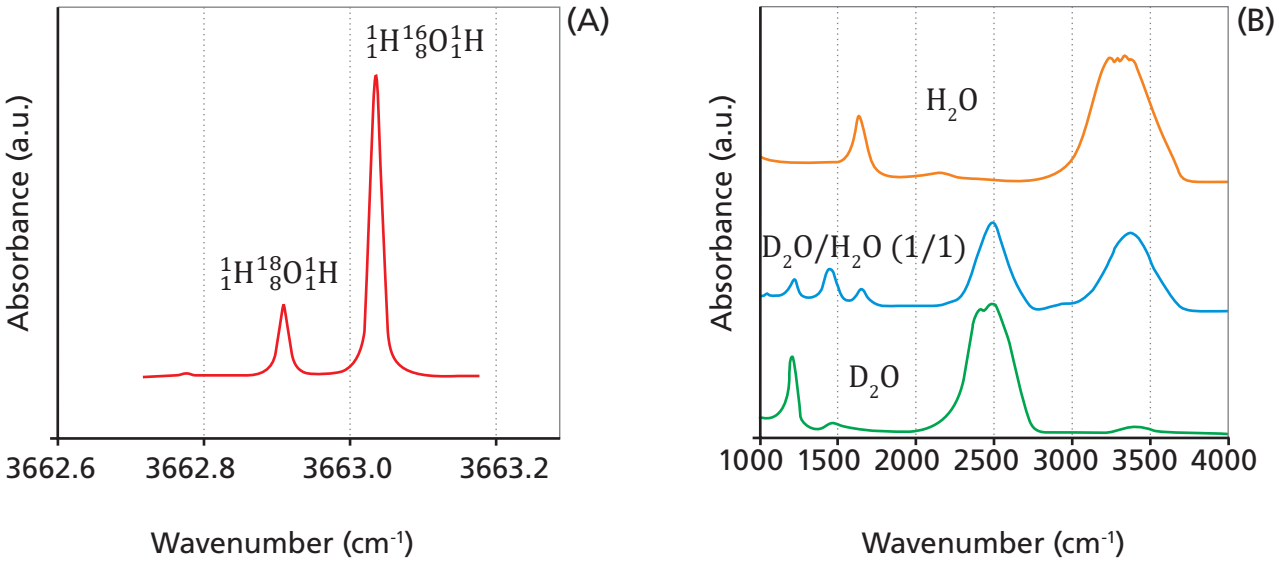
Laser Absorption Spectroscopy

A recently developed device is the Laser Absorption Spectrometer (LAS), which works based on the fact that when illuminated with an infrared emitting laser, the molecules absorb the frequencies corresponding to their natural vibrations.

The molecules can be compared to mass-spring systems, where the atoms would be the masses and the bonding forces between them would be the springs. These systems may oscillate by rotation of the "masses", compression or bending of the "springs". The vibration frequencies are characteristic of each molecule, and have frequencies in the infrared range. Thus, if there are molecules in a sample that differ by the presence of isotopes of the same atom, the vibration frequencies will be slightly different, and the absorption spectrum of the sample will show different peaks.

Figure II-3 shows examples of absorption spectra for water samples containing different isotopes. The larger the isotope mass, the lower its vibration frequency.

Figure II-3: Infrared absorption spectra of water samples



Based on: van Trigt, R .: Thesis Rijksunivesiteit Groningen (2001) available at: <https://www.rug.nl/research/portal/files/3035350/thesis.pdf>. Accessed Jan 2019.

Based on: Vanderkooi, J. M. et al .: Biochimica et Biophysica Acta - Proteins and Proteomics, 1749 (2), 214-233 (2005).

In the horizontal axis, the wavenumber is plotted, which corresponds to the inverse of the wavelength and therefore is proportional to the frequency of the light absorbed. In the vertical axis, the absorbance is plotted in arbitrary units. In A, the sample contains $^{1}_{1}H^{16}_{8}O^{1}_{1}H$ and $^{1}_{1}H^{18}_{8}O^{1}_{1}H$. Note that the absorption peak of the lower mass isotope is at a higher frequency (rotational / vibrational mode). In B, the spectrum of a composite sample is compared to the spectrum of a pure sample of $^{1}_{1}H^{16}_{8}O^{1}_{1}H$ and another of $^{2}_{1}H^{16}_{8}O^{2}_{1}H$. Similarly to the previous case, it is observed that the isotope of lower mass vibrates with greater frequency (symmetrical stretching mode).[4]

LAS devices are compact and easy to carry, facilitating their use in field surveys. They can be calibrated to automatically calculate the ratio of the desired isotopes. However, different equipment will be required for samples containing H_2O, CO_2 or N_2O (measurements of H, O or C). The mass spectrometer is preferentially used for the analysis of N or S.

Applications

Oxygen isotopes

Information on surface and groundwater

The isotopic analysis of the waters of rivers, lakes and underground reserves can lead to knowledge about the interaction among these hydrologic systems. This information is valuable in accompanying and administering the collection and use of water.

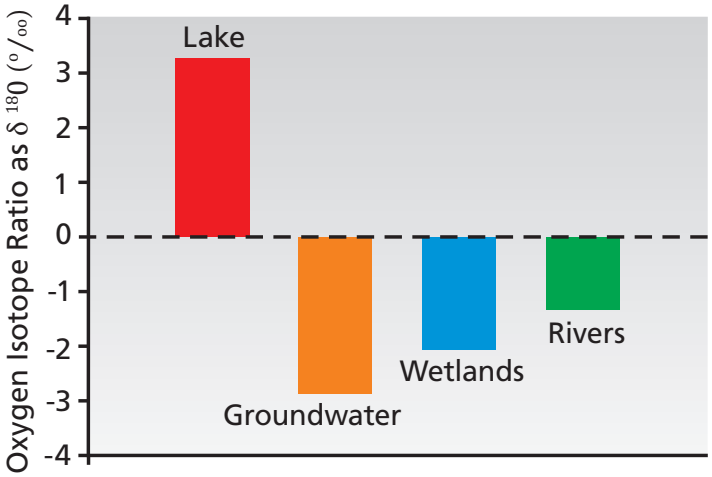
An interesting example may be seen in Figure II-4, which shows the isotopic ratio $\delta^{18}O$ for Lake Victoria,[5] in Africa, as well as to the wetlands, rivers and groundwater surrounding it. From the data shown, it is possible to conclude that the water of the lake undergoes evaporation and precipitation, but the lake is not supplied by the underground reserve nor by the adjacent rivers. In addition, it can also be concluded that the water present in the wetlands is supplied by the underground reserve, not by lateral flow of the waters from the lake.

---

[4] $^{2}_{1}H$ (hydrogen nucleus with 1 proton and 1 neutron) is called deuterium, for which the symbol D is used.

[5] Lake Victoria is one of Africa's largest lakes, located between Tanzania, Kenya and Uganda.

Figure II-4: isotope ratio $\delta^{18}0$ for Lake Victoria (Africa) and for the surrounding waters



The positive ratio for the lake indicates that it mainly undergoes evaporation and precipitation and is not supplied by the underground reserve or the rivers, which have $\delta^{18}0$ negative. The wetlands have $\delta^{18}0$ negative, indicating that they are supplied by groundwater and not by lake overflow.
Based on document IAEA - Water Resources Program.

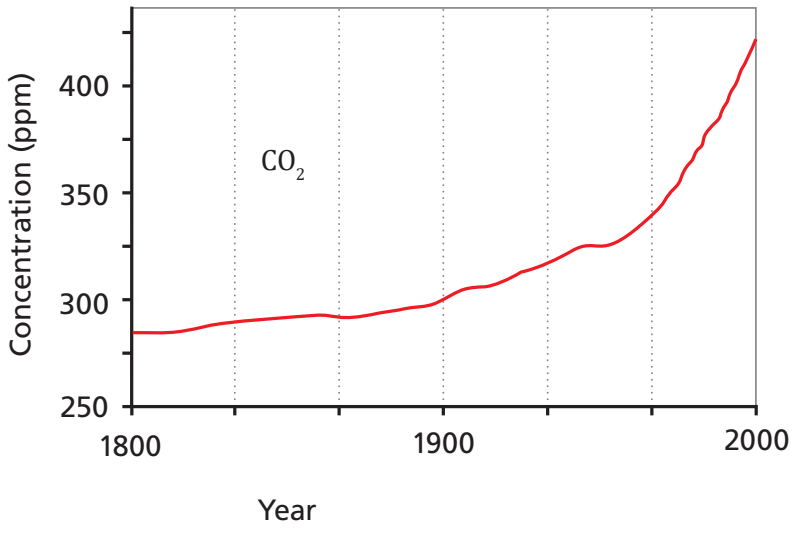
Carbon Isotopes

Origin of carbon in the atmosphere

The presence of CO_2 in the Earth's atmosphere is mainly due to the respiration of living beings or the decomposition of their remains. Although its concentration is low, this gas is useful because it causes a beneficial "greenhouse effect", which prevents some of the heat from the sun absorbed on the surface of the globe from escaping back into space. This helps keep Earth's temperature at levels that are convenient for life maintenance. However, if the CO_2 concentration in the atmosphere increases, excessive heat retention can occur, resulting in imbalance of the climate and harm to living beings.

The concentration of carbon dioxide in the Earth's atmosphere remained constant over a long period of time, around 0.028%. However, in the last 150 years, there has been an increase in this concentration, which now reaches 0.040%, which means an increase of 30% (Figure II-5). Through measurements of the carbon isotope ratio, it is possible to study the cause of this increase.

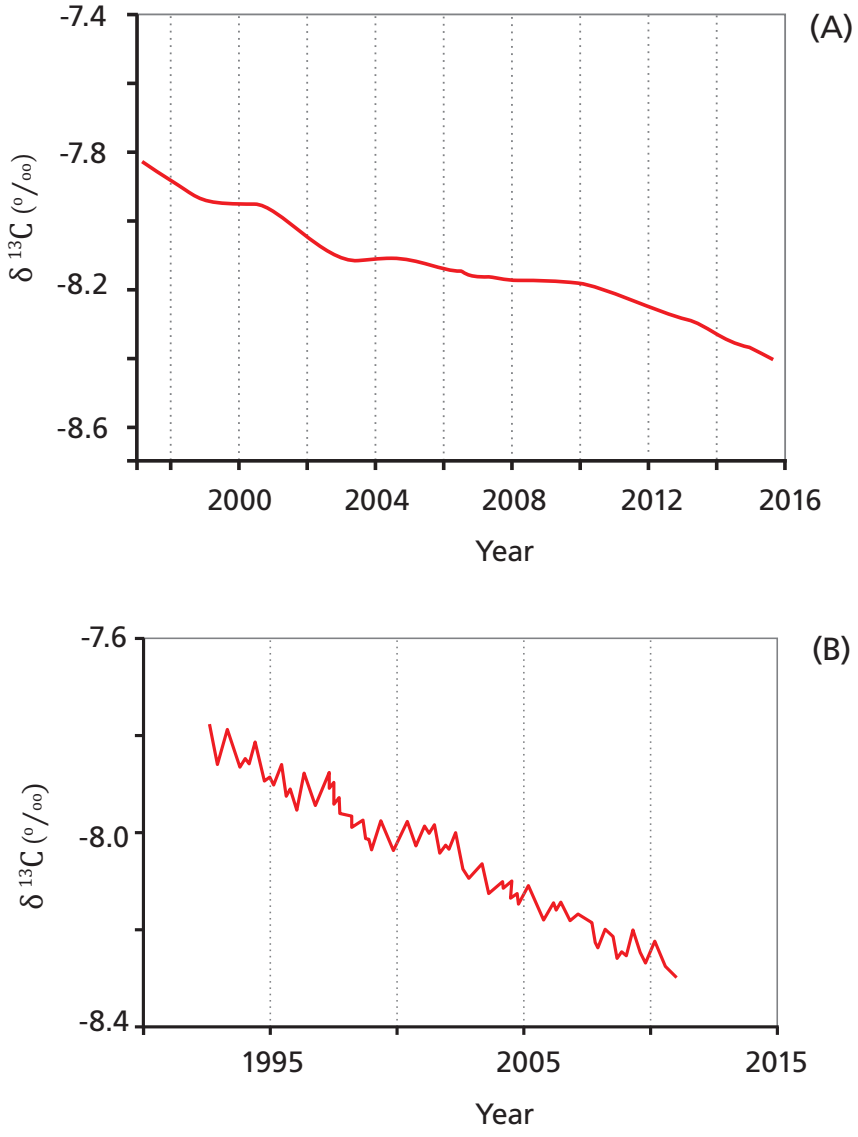
Figure II-5: Variation of CO_2 concentration in the Earth's atmosphere over time



Based on data from the European Environment Agency (EEA), available at: <https://www.eea.europa.eu/data-and-maps/indicators/atmospheric-greenhouse-gas-concentrations-10/assessment>. Acessed Jan 2019.

Measurements of $\delta\,^{13}C$ in the atmosphere, as shown in Figure II-6, indicate that this value decreased over time, although the CO_2 concentration increased.[6] Plants are known to more easily absorb from the air the carbon dioxide composed of lighter isotopes. The isotopic ratio of carbon in plants is therefore different from that in the atmosphere. Over time, the dead plants were buried and transformed into fossil fuels, keeping the same isotopic ratio. The burning of this fuel then releases into the atmosphere carbonic gas with a smaller proportion of ^{13}C in relation to ^{12}C. The decrease in the value of $\delta\,^{13}C$ in the atmosphere leads, therefore, to the assumption that the increase in carbon dioxide released into the atmosphere is due to the burning of fossil fuels, a hypothesis corroborated by the fact that this trend has been noticed since the beginning of the Industrial Revolution.

Figure II-6: Variation of the isotopic ratio $\delta\,^{13}C$ in CO_2 of the atmosphere, as a function of time, measured in Antarctica (A) and Australia (B)



Based on data from NIWA (National Institute of Water and Atmospheric Research, New Zealand), available at: <https://www.niwa.co.nz/atmosphere/our-data/trace-gas-plots/carbon-dioxide>. Acessed Jan 2019.

[6] Both the concentration of CO_2 as the value of $\delta\,^{13}C$ in ancient times can be inferred by measurements made in ancient tree trunk rings, in sea corals or sponges, or in the air trapped in the ice at the poles.

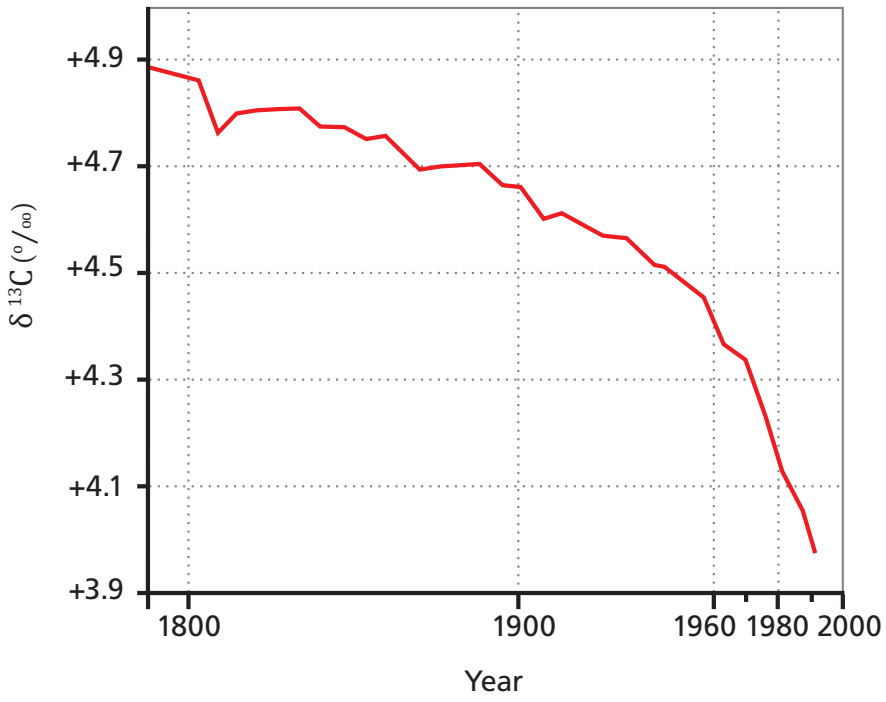
Origin of carbon in the oceans

Part of the carbon dioxide released into the atmosphere dissolves in ocean waters or is absorbed by microalgae, on the surface of the oceans, and transformed into organic molecules. Eventually, the carbon of organic origin is deposited at the bottom of the ocean.

The pumping of CO_2 from the atmosphere by the oceans is useful to maintain stable levels of carbon dioxide in the atmosphere, but the excess of this gas dissolved in the oceans can lead to acidification of the oceans, harming sea life.

There is currently an increase in the CO_2 concentration in the oceans, and isotopic carbon analysis in corals and sponges indicates a decrease over time in the value of $\delta\ ^{13}C$ (Figure II-7), which may be further evidence that excess carbon dioxide is due to the burning of fossil fuels.

Figure II-7: Variation of isotope ratio $\delta\ ^{13}C$ in CO_2 of marine sponges, as a function of time, measured in Jamaica



Based on data from F. Böhm et. al. [Earth and Planetary Science Letters 139 (1-2), 291 (1996)], available at: <http://www.realclimate.org/images/bohm_corals_13C.jpg>. Acessed Jan 2019.

Nitrogen and sulfur isotopes

Isotopic compositions of nitrogen and sulfur can be used to determine the presence of pollution in water or pesticides in food. This is possible because detergents, medicines and chemicals used in industry and agriculture contain large amounts of nitrates and sulfates. The chemical reactions used for the production of these substances occur at different speeds for isotopes of different masses, and therefore, there is a variation in the values of $\delta\ ^{15}N$ and $\delta\ ^{34}S$.

Isotope measurements can inform if the nitrogen and sulfur contained in water and food are of natural origin or come from artificial pollutants.

Acknowledgments: We thank the collaboration of L. Araguas-Araguas and Manfred Groening (IAEA) in the preparation of this chapter.

CHAPTER III - APPLICATION OF NUCLEAR ENERGY IN INDUSTRY

Radioisotopes have several industrial applications, such as in chemical, petroleum or mining industries. This chapter describes three of the most common uses in industry: radiotracers, nucleonic control systems and non-destructive testing.

Radiotracers

Radiotracers are radioisotopes incorporated into a system and monitored to indicate the movement of the fluid or solid to be studied. They are widely used in the chemical and petroleum industries, as well as environmental process studies. Radioactive tracers are interesting because the detectors are very sensitive, allowing the use of very low concentrations of the radioelement. The detectors used are portable, and measurements can be made *in loco*.

The radiotracer must have physical and chemical properties similar to those of the material to be traced, and its half-life must be compatible with the measurement time: if the half-life is too short, it will not be possible to prepare, transport, introduce the tracer at the test site and perform the measurement before the activity falling to non-measurable values; if the half-life is too long, radioactive material will remain in place after the end of the analysis.

Radiotracers in the oil industry

In the oil industry, radiotracers may be used to detect pipeline leaks due to cracks or failures in connections. Since water is normally injected under high pressure to facilitate the extraction and transport of oil, it is possible to use water-soluble radiotracers. These may be soluble salts, such as KBr containing bromine-82, or tritiated water (water where one or both hydrogen atoms have been replaced by tritium).

^{82}Br can be obtained by neutron bombardment of the stable isotope ^{81}Br:

$$^{81}_{35}\mathrm{Br} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{82}_{35}\mathrm{Br} + \gamma$$

Bromine-82 decays by β^- emission into the stable element krypton-82:

$$^{82}_{35}\mathrm{Br} \rightarrow {}^{82}_{36}\mathrm{Kr} + {}^{0}_{1}\beta^- + \bar{\nu}_e \qquad T_{1/2} = 35\ \mathrm{h}$$

The half-life of bromine-82 is long enough to allow for element activity to be observed, for example during work in a refinery; after the measurements, the radiotracer will be at a very low level, leaving no radioactive waste in the environment.

Tritium (hydrogen atom with 2 neutrons and a proton) is the only radioactive isotope of hydrogen. Although its half-life (12.3 years) is short compared to the Earth's age, it exists in nature because it is created in the upper atmosphere by the bombardment of nitrogen by cosmic rays. Its chemical behavior is the same as that of the hydrogen atom and therefore tends to bind with oxygen to form tritiated water, which is also called tritium oxide (THO, TDO or T_2O).[7] The concentration of natural tritium is very low (1 atom of T for 10^{18} atoms of H), but it can also be obtained artificially, for example, by the activation of lithium-6 by neutrons:

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

The process is accomplished by subjecting lithium-containing ceramics to the neutron flux of a nuclear reactor.

Tritium decays into helium-3 (stable) with β^- emission:

$$^{3}_{1}\mathrm{T} \rightarrow {}^{3}_{2}\mathrm{He} + {}^{0}_{-1}\beta^- + \bar{\nu}_e \qquad T_{1/2} = 12.3\ \mathrm{years}$$

The advantages of using tritium oxide as a radiotracer are its chemical behavior, identical to that of water, and the fact that in its decay there is no γ emission, only low energy β^- emission, which is easily shielded. The disadvantage is that the energy of the emitted radiation is low: it is at most 18.6 keV, with an average value of 6 keV. For its detection, it is necessary to add the tritiated water sample to a liquid scintillation detector, which emits fluorescent light in response to β^- radiation. This procedure needs to be carried out in the laboratory.

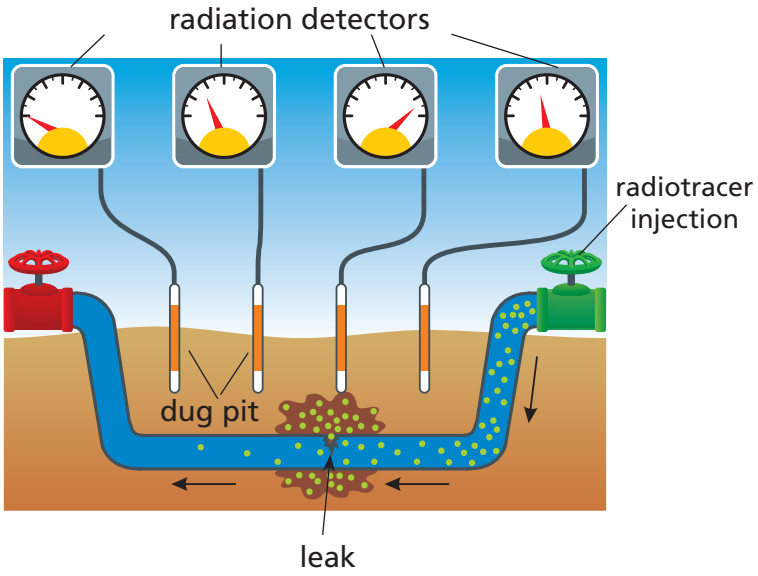
Although the half-life of tritium is relatively long, compared to the time of measurements in the industry, the residue is not harmful to humans or the environment. This is due to the fact that the energy of its emission is very low, and the radiation has low penetration (it does not penetrate, for example, the human skin). In the case of ingestion, tritium is rapidly eliminated from the body in water molecules, mainly through the urinary tract.

Figure III-1 illustrates the procedure for pipe leakage detection using a radiotracer and detectors buried along the pipe. In Figure III-2, it is shown the detection method using a radiotracer pig that moves inside the pipe.

---

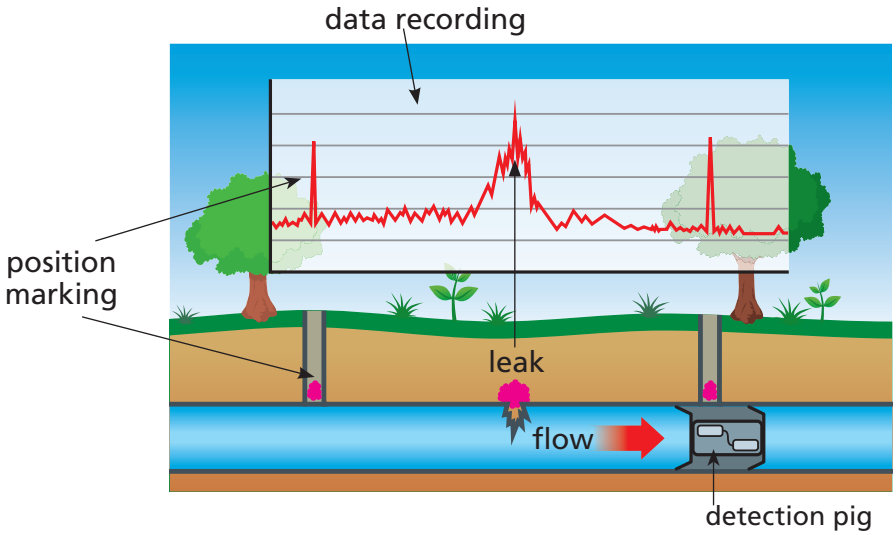
[7] The T symbol is used for tritium (hydrogen with 2 neutrons and 1 proton) and D for deuterium (hydrogen with 1 neutron and 1 proton).

Figure III-1: Detection of leakage in a pipeline using radiotracer and buried detectors



The radioisotope is injected into a section of the pipeline and subsequently the reading is made using the detectors buried in the pipe path. If there is a leak or blockage in the pipeline, the radioisotope will be trapped at the leak point and the detectors located downstream will not record any activity. Based on a document provided by Patrick Brisset (IAEA).

Figure III-2: Detection of leakage in a pipeline, using radiotracer and a detection pig

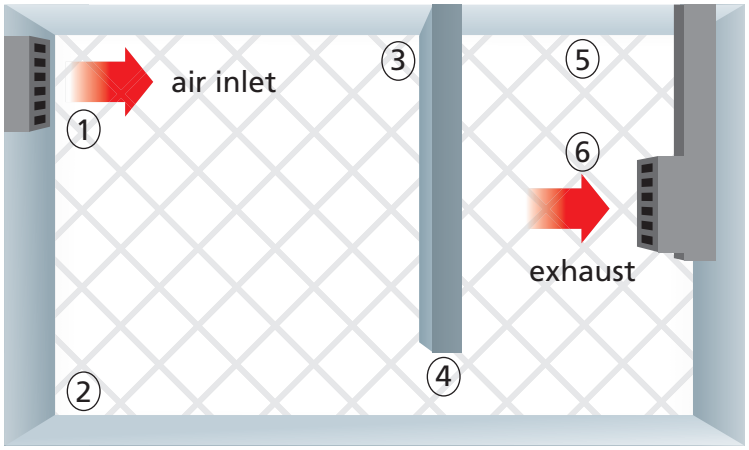


The radioisotope is injected into the pipeline and travels along the line together with the fluid. If there is a leak, the radioisotope will accumulate in that area. The pig is then inserted into the pipeline. As it moves along with the fluid, it records the activity and is collected at the end of the path. At regular intervals, buried sources indicate the distances traveled. Based on a document provided by Patrick Brisset (IAEA).

Gaseous flows

The monitoring of gaseous flows is important in the oil industry, gas pipelines, and the chemical industry, in catalytic fractionation columns or in environments with controlled airflow and exhaust (Figure III-3).

Figure III-3: Use of radiotracer to monitor the airflow in an industrial environment



The tracer is inserted through the air intake and its activity is measured at different points in the room (points 1 to 6); the tracer is later eliminated along with the exhaust air. Based on an IAEA document available at: <https://www-pub.iaea.org/MTCD/Publications/PDF/TRS423_web.pdf> (pg. 141). Accessed Jan 2019.

An example of a gaseous radiotracer is krypton-79, a noble gas that can be obtained by bombarding selenium-76 with α particles:

$$^{76}_{34}\mathrm{Se} + {}^{4}_{2}\alpha \rightarrow {}^{79}_{36}\mathrm{Kr} + {}^{+1}_{0}\beta^{+} + \nu$$

Another way of obtaining it is by bombarding bromine-79 with protons using an aqueous solution of sodium bromide (NaBr):

$$^{79}_{35}\mathrm{Br} + {}^{1}_{1}\mathrm{p} \rightarrow {}^{79}_{36}\mathrm{Kr} + {}^{1}_{0}\mathrm{n}$$

Krypton-79 decays into bromine-79 with β^{+} emission:

$$^{79}_{36}\mathrm{Kr} \rightarrow {}^{79}_{35}\mathrm{Br} + {}^{0}_{1}\beta^{+} + \nu \qquad T_{1/2} = 35\mathrm{h}$$

In order to obtain α particles or proton beams, it is necessary to use accelerators. Another way to produce radioactive krypton is by neutron irradiation of krypton-84 in a nuclear reactor, thus obtaining krypton-85 ($T_{1/2} = 4.5$ h), more suitable for ventilation studies. The stable isotope $^{84}\mathrm{Kr}$ is the most abundant of the seven natural isotopes of krypton (isotopic abundance ~ 57%) and irradiation in a reactor is often more practical than using an accelerator. The reactions for production and decay of krypton-85 are:

$$^{84}_{36}\mathrm{Kr} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{85}_{36}\mathrm{Kr}$$

$$^{85}_{36}\mathrm{Kr} \rightarrow {}^{85}_{37}\mathrm{Rb} + {}^{0}_{-1}\beta^{-} + \bar{\nu} \qquad T_{1/2} = 4.5\ \mathrm{h}$$

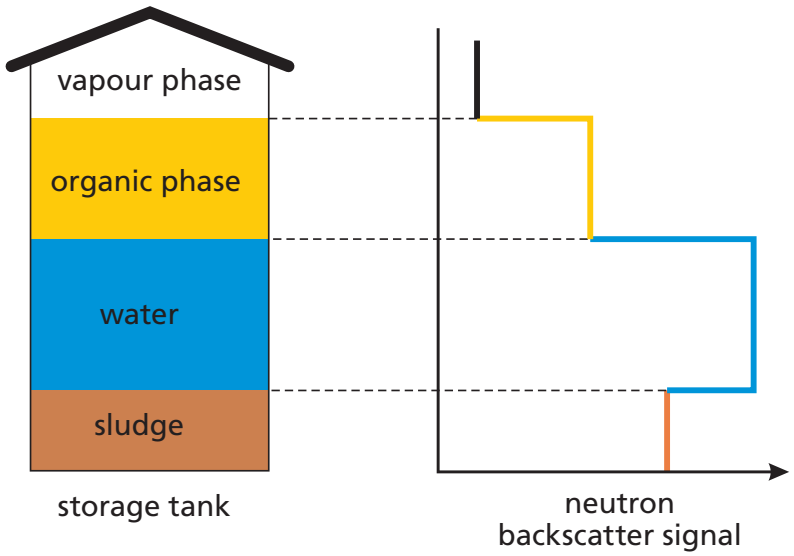
Nucleonic control systems

Nucleic Control Systems (NCS) are systems where ionizing radiation (α, β, γ, X or n) focuses on the material to be analyzed, and information on the material is obtained through the interaction between the material and the radiation using appropriate detectors. This allows the control of some physical properties of the material, such as density, mass, chemical composition, moisture content, etc. Examples of the NCS are the moderation and backscattering of neutrons, the analysis of neutron activation of immediate γ rays (prompt γ neutrons), the analysis by dual-energy γ emission measurements, and gamma backscattering, tomography or scanning.

Neutron backscattering

In this technique, a fast neutron beam is directed at the material to be analyzed. When colliding with hydrogen nuclei from the material, the neutrons lose energy (they are moderated); direct shocks cause some neutrons to be reflected back and to lose some of their energy. A slow neutron detector is placed next to the source and records the backscattered neutron intensity, which is proportional to the density of hydrogen atoms in the material. By moving the source and detector along the vessel it is possible to know, for example, the levels of liquids and/or gases in columns, the separation of phases, presence of precipitation or impurities etc. The source and detector are placed on the outside of closed containers and the analysis can be performed without interrupting the processing of the material. Figure III-4 illustrates the use of neutron backscattering in an oil tank to determine its internal contents.

Figure III-4: Neutron backscattering in an oil tank



Each phase of the material can be recognized by the backscattered neutron intensity, which is proportional to the density of hydrogen atoms present in that phase. Based on IAEA document, available at: <https://gnssn.iaea.org/RTWS/general/Shared%20Documents/Radiation%20Protection/CS%20on%20Radiotracers,%2020-24%20February%202017/Review%20paper%20Radioisotope%20applications.Rev%20PB%2013%20sept%202013.pdf>. Accessed Jan 2019.

The neutron source commonly used in this technique is composed of an americium-241 oxide tablet, pressed with metallic beryllium-9. Americium is a transuranic element[8] which may be obtained in a reactor by bombardment of uranium-238 with neutrons, thus causing a series of γ and β^- emissions:

$$^{238}_{92}U \xrightarrow{n,\gamma} {}^{239}_{92}U \xrightarrow{\beta^-} {}^{239}_{93}Np \xrightarrow{\beta^-} {}^{239}_{94}Pu \xrightarrow{2(n,\gamma)} {}^{241}_{94}Pu \xrightarrow{\beta^-} {}^{241}_{95}Am$$

[8] Transuranic elements are elements that have atomic numbers greater than that of uranium. They are unstable and do not exist in nature, but can be obtained artificially in the laboratory.

Americium-241 decays by α emission:

$$^{241}_{95}\text{Am} \rightarrow {}^{237}_{93}\text{Np} + {}^{4}_{2}\alpha + \gamma \qquad T_{1/2} = 432 \text{ years}$$

Beryllium absorbs the α particle and forms carbon-12, emitting a fast neutron:

$$^{9}_{4}\text{Be} + {}^{4}_{2}\alpha \rightarrow {}^{12}_{6}\text{C} + {}^{1}_{0}\text{n} + \gamma$$

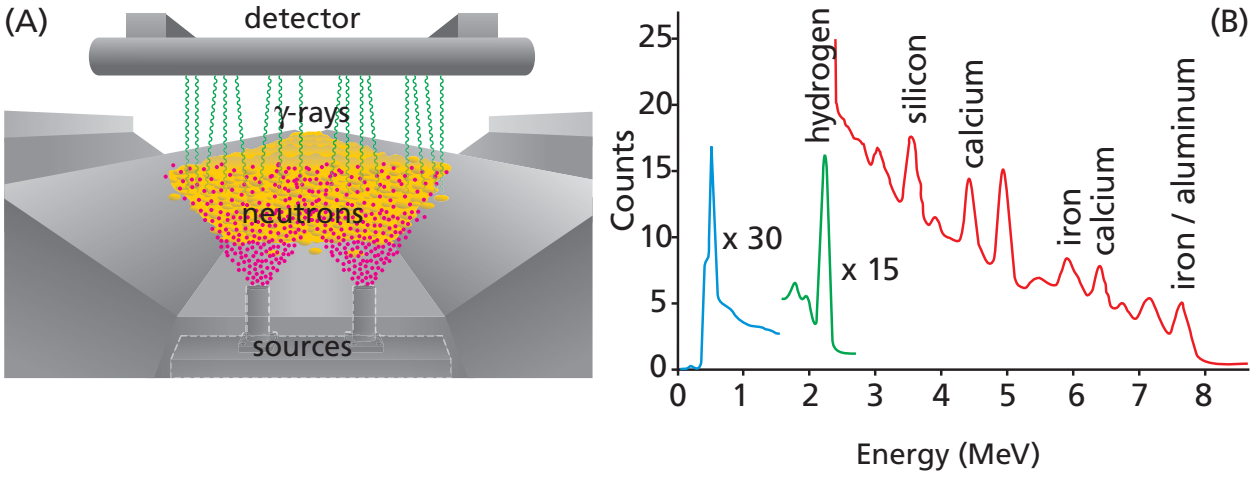
The energy of the emitted neutrons is around 4 MeV.

PGNAA

The PGNAA (Prompt Gamma Neutron Activation Analysis) is a technique used in mining or in the cement industry, for analysis of material while being transported on conveyor belts (Figure III- 5A).

Thermal neutron sources[9] are placed below the conveyor belt. When the neutrons strike the material, they are absorbed by the nuclei, which are excited and decay to their ground state with γ emission. Each element present in the material to be analyzed has γ emission with well-defined energy, whose intensity is proportional to the concentration of the element; γ detectors placed above the conveyor then indicate the presence and concentration of each component (Figure III-5B). Neutrons are very penetrating, allowing the analysis of the entire thickness of the material on the belt.

Figure III-5: Prompt gamma neutron activation (PGNAA)

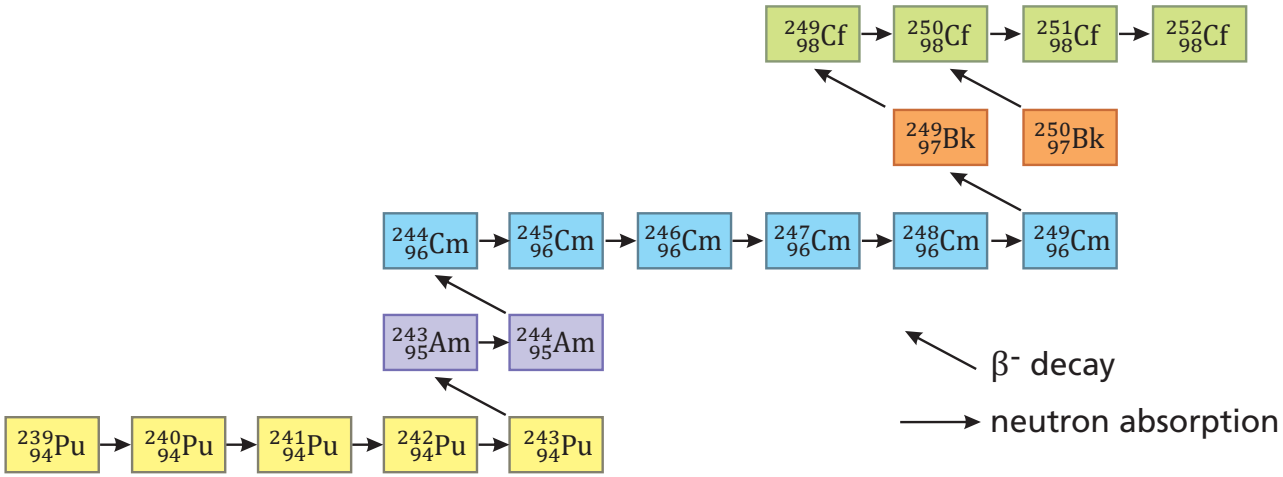


A: Equipment diagram. B: Energy spectrum in cement analysis. Based on Thermofisher Scientific document, available at: <https://www.thermofisher.com/br/en/home/industrial/cement-coal-minerals/cement-coal-minerals-learning-center/cement-analysis-production-information/pgnaa-pftna-technology.html>. Accessed Jan 2019.

The neutron source used in PGNAA is californium-252. Californium is a transuranic element that can be obtained from plutonium, in a nuclear reactor, through a sequence of neutron absorptions and β^- decays (Figure III-6).

[9] Thermal neutrons are neutrons in thermal equilibrium with the environment; this means that they have energies of the order of $^{3}/_{2}$ KT (around 0.04 eV or 6×10^{-21} J)

Figure III- 6: Obtaining Cf-252 from Pu-239, by means of a neutron absorption and β^- decay sequence



The chain of events is very long, which explains the huge loss of material during the obtention process. This difficulty in obtaining and handling the material makes it extremely expensive, about US$30×10^6 a gram. However, as it is a strong neutron emitter, the amount used in measurement equipments is of the order of micrograms (μg).

Californium is unstable and decays by emission of α particles or by fission; in the latter case, there is the generation of a large number of neutrons, as in the example below:

$$^{252}_{98}Cf \rightarrow {}^{102}_{40}Zr + {}^{146}_{58}Ce + 4\,^{1}_{0}n$$

The emitted neutrons have high energy levels (on average, 0.7 MeV, and can reach up to 2.6 MeV) and must be thermalized before hitting the material to be analyzed. To achieve this, the radioactive element is encased in material composed of a large quantity of hydrogen atoms (ceramics or polymers).

Another source of neutrons used in PGNAA is americium-241, already described in this chapter.

It is also possible to obtain neutrons through the fusion of deuterium and tritium, forming helium and releasing neutrons:

$$^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{2}He + {}^{1}_{0}n + 3.3\ MeV$$

$$^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n + 17.6\ MeV$$

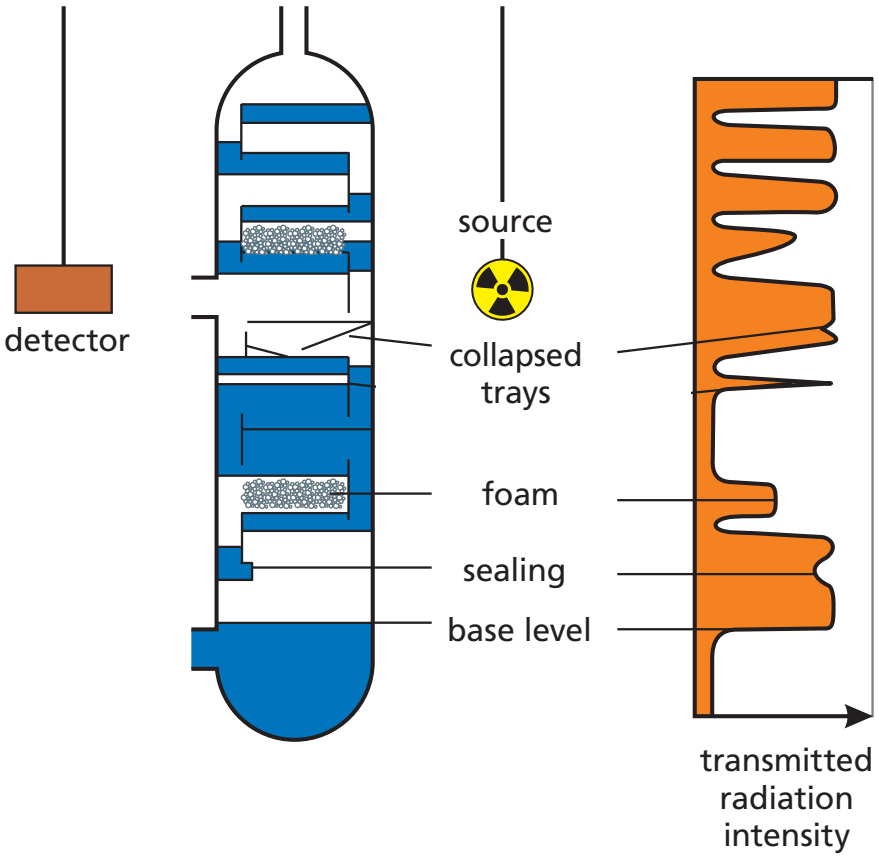
Since the PGNAA measurements need thermal neutrons, these formidable energies must be moderated by a factor of the order of 10^9. This is done by introducing special materials consisting of light atoms (e.g. paraffin) between the source and the material to be analyzed.

For the fusion reactions to occur, an accelerator is needed to provide the nuclei with enough energy to overcome the electrostatic repulsion between them. Neutron generators based on the D-T fusion are already being marketed and will provide a much more affordable and lower-cost neutron source than nuclear reactors.

γ Scanning

The attenuation of γ rays depends on the density and thickness of the material they traverse. Therefore, it is possible to obtain information about the interior of an enclosed container using appropriate sources and detectors. In the case of γ scanning, the source is placed on one side of the container, and the detector on the opposite side; they move together allowing a scan of the entire container (Figure III-7). This technique is useful to reveal the level of the various phases present inside a distillation column, as well as defects in its internal structure. The most commonly used sources are ^{137}Cs or ^{60}Co; NaI(Tl) scintillators are used as detectors.

Figure III-7: Profile of an oil industry column, achieved by γ scanning



The γ source is placed on one side of the column, and the detector on the opposite side. Since the γ transmitted intensity depends on the density of the traversed material, it is possible to map the internal structure of the column and to detect the presence of liquid or foam. Based on A. Jaafar, Hydrocarbon Asia Jan / Feb, 62-65 (2005) available from: <http://scanningtech.com/PDF/article3.pdf>. Accessed Jan 2019.

Dual-energy Gamma Radiation Analysis

Gamma absorption is often used to learn the shape of an object or structure inserted in a container, but the profile obtained can be compromised, if the several phases involved have very close γ attenuation indices, which makes it difficult to establish clear boundaries between the phases. This problem can be overcome by using two different γ emissions with different energies.

The attenuation profile of each material depends on the energy of the radiation; combining the results obtained with radiation of different energies, it is possible to obtain more precise information about the inside of the container.

Dual transmission is also useful for analysis of conveyor-transported mining products, where the thickness of the material transported may hinder the transmission of radiation through higher density components.

Non-destructive tests

Non Destructive Testing (NDT) refers to tests that do not change the material being analyzed. These tests often use the absorption of electromagnetic radiation or sound to obtain information about the interior of a vessel. Radiographic NDT includes imaging through γ-rays, X-rays and, more seldom, neutron beams. Recently, analysis using muons (energetic particles coming from space) has been used for the study of large structures.

X-rays and γ-scans

After traversing a material, the X and γ-rays are attenuated according to the density and thickness of that material. By measuring the intensity of the radiation that has passed through an object, it is possible to transform the information obtained into images that illustrate its interior. This technique is widely used in medical applications, baggage control at airports, checking the internal structure of containers, industrial machines, sculptures, antique objects, etc. (Figure III-8). The generation of X-rays requires large-sized fixed equipment and a source of electric power. When it is necessary to make the emission source mobile, it may be more convenient to use γ sources, usually cobalt-60 or cesium-137. In addition, γ-rays are more energetic and therefore more penetrating than X-rays, providing more information in the case of very thick objects.

Figure III-8: Gammagraph of the engine gear of a turbine, showing a crack in its interior

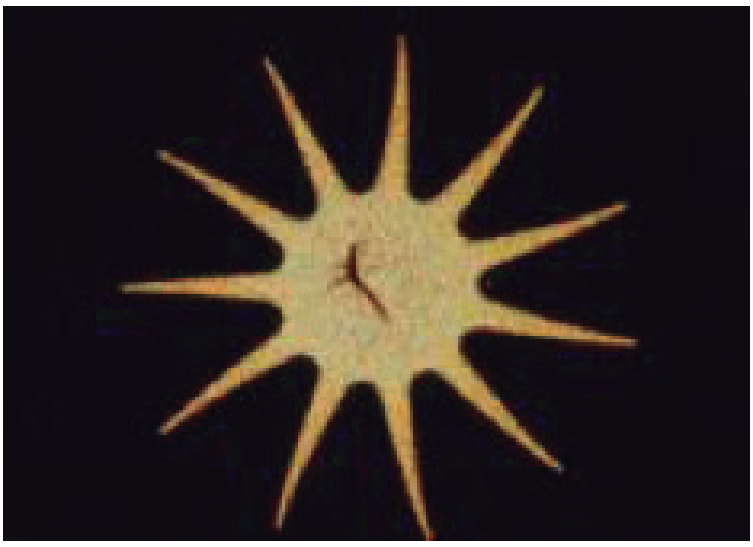


Photo: Commissariat à l'Énergie Nucléaire - CEA-CADAM (France). Source: <http://www.radioactivity.eu.com/site/pages/Non_Destructive_Testing.htm>. Accessed Jan 2019.

In radiography and γ scanning, the information is acquired by scintillator detectors and the data is then processed in computers to provide an image of the object.[10]

[10] Prior to the development of computational methods, the detection of X or γ-rays was done using photographic films, sensitive to radiation. Today, these films are still used in special situations.

In tomography, images made at different angles and positions can be grouped to provide a three-dimensional view of the object.

Other applications of ionizing radiation

In addition to the examples already mentioned, new applications of nuclear energy in industry as well as in other areas are developed every day. Through γ irradiation, for example, it is possible to cure polymer materials by changing their structure (with the formation of bonds between the polymer chains).

Acknowledgments: We wish to thank researchers Rubens Martins Moreira and Jefferson Vianna Bandeira (CNEN, Brazil), João Alberto Osso Júnior, Patrick Brisset and Sabharwal Sunil (IAEA) for their collaboration in the preparation of this chapter.

CHAPTER IV - ENVIRONMENTAL STUDIES

The environment of coastline regions and river banks is subject to considerable modification, not only as a result of climatic events but also due to human intervention, leading to sediment accumulation or erosion.

The study of the transport of sediments in aqueous environments is important, for example, in the construction and maintenance of ports and dams, where it is necessary to know if the sediments are transported by the water flow or if they are accumulated in place, in order to optimize the design.

One of the techniques for studying the movement of water and sediments in ports, dams or water bodies is the use of radioactive tracers. These can be added to samples taken *in loco*, which are then released and monitored as the labelled material is carried along. The labelling can be performed on the sludge in aqueous suspension, on the liquid effluent itself or on the deposited sediments. Radiation measurements are very sensitive and therefore only minimal amounts of radioactive tracer are necessary.

In some studies, the sediment is labelled with non-radioactive elements; later, samples are collected in the vicinity of the discharge site and nuclear techniques may determine the presence of the tracer element and its quantity.

Another possibility is the use of sealed source techniques to provide information on the density of sediments deposited in a navigation channel or concentration of sediments circulating in suspension. The radiation will be absorbed or scattered by the sediments, indicating their characteristics. These analyses are non-destructive and do not interfere with the natural flow of sediments.

Environmental studies can also use nuclear techniques to observe the movement of natural or man-made radioisotopes.

Radioactive tracers

Use of gold as a radiotracer

For studies of soil erosion and sediment movement in the ocean, in port channels or in water ways, one can label clay or fine sand with gold-198, a radioactive element with a relatively short half-life (2.7 days). The particles of a sediment sample are pretreated with a stable gold solution in the form of auric acid, and the gold element is adsorbed on its surfaces. Then, the sample is irradiated, creating a radiotracer with properties similar to those of the sediment. The finer the particles, the greater the ratio between their surface and their volume and, therefore, the more efficient the gold labelling. The labelled material is scattered in small proportions (in a concentration of parts per billion) over the surface to be studied and subsequently traced using appropriate detectors.

^{198}Au is obtained by neutron bombardment of metallic ^{197}Au:

$$^{197}_{79}\mathrm{Au} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{198}_{79}\mathrm{Au} + \gamma$$

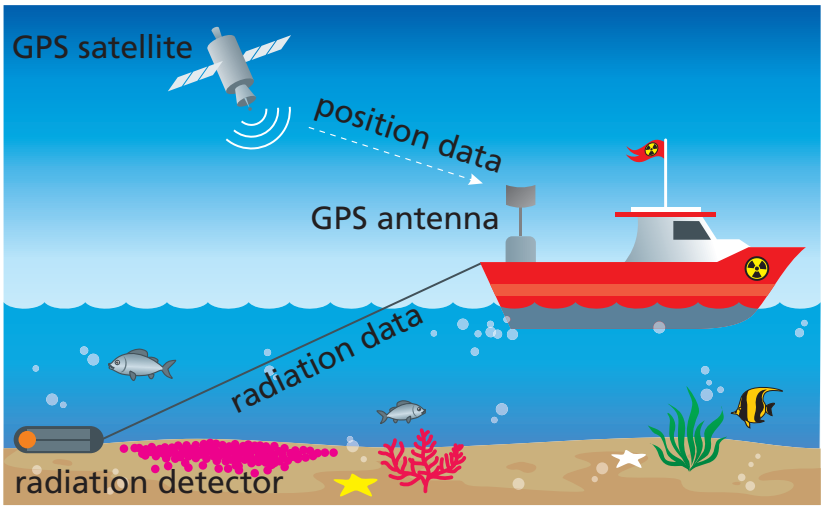
^{198}Au decays into ^{198}Hg, which is stable:

$$^{198}_{79}\mathrm{Au} \rightarrow {}^{198}_{80}\mathrm{Hg} + {}^{0}_{-1}\beta^{-} + \bar{\nu}_e + \gamma \qquad T_{1/2} = 2.7 \text{ days}$$

The β radiation is easily shielded by the surrounding material. The most abundant γ radiation emitted during ^{198}Au decay has energy values around 0.4 MeV.

Figure IV-1 shows an example of the use of radiotracers to study sediment transport in sea beds.

Figure IV-1: Acquisition of data about sediment transport in the seabed



After insertion of the radiotracer in the studied region, a detector is placed on the seabed and pulled by a vessel that receives the activity data. The location of the active region is determined by GPS. Based on IAEA document, available at: <https://gnssn.iaea.org/RTWS/general/Shared%20Documents/Radiation%20Protection/CS%20on%20Radiotracers,%2020-24%20February%202017/Review%20paper%20Radioisotope%20applications.Rev%20PB%2013%20sept%202013.pdf>. Accessed Jan 2019.

The disadvantage of the use of gold-198 as a tracer is that it must be produced in a nuclear reactor, not always available near the studied site. In addition, the γ emission energy is relatively high (400 keV) and requires care in the transport and handling of the material.

When the sediment movement is very slow, tracers with longer half-lives are used, for example, chromium-51 ($T_{1/2}$ = 27 days) or iridium-192 ($T_{1/2}$ = 73 days).

Technetium-99m used as a radiotracer

An alternative for the labelling of fine sediments is the use of technetium-99m. This element is commonly used in radiological testing.[11] It is obtained by the decay of molybdenum-99, a fission product of uranium-235 which can be chemically separated from other fission products:

$$ {}^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow ({}^{236}_{92}\mathrm{U}^{*}) \rightarrow {}^{99}_{42}\mathrm{Mo} + {}^{134}_{50}\mathrm{Sn} + 3{}^{1}_{0}\mathrm{n} + \mathrm{E} $$

$^{99}\mathrm{Mo}$ decays into $^{99\mathrm{m}}\mathrm{Tc}$ with a half-life of 66 hours and can be transported to the place of use, where the technetium is extracted from the Mo/Tc mixture:

$$ {}^{99}_{42}\mathrm{Mo} \rightarrow {}^{99\mathrm{m}}_{43}\mathrm{Tc} + {}^{0}_{-1}\beta^{-} + \bar{\nu}_{\mathrm{e}} \qquad T_{1/2} = 66\ \mathrm{h} $$

$^{99\mathrm{m}}\mathrm{Tc}$ decays into $^{99}\mathrm{Tc}$ with half-life of 6 hours, through γ emission, with energy of 140 keV:[12]

$$ {}^{99\mathrm{m}}_{43}\mathrm{Tc} \rightarrow {}^{99}_{43}\mathrm{Tc} + \gamma \qquad T_{1/2} = 6\ \mathrm{h} $$

Because the half-life of molybdenum-99 is 10 times greater than that of technetium-99m, it is possible to obtain technetium for medical diagnostics up to one week after the arrival of the material; after this time, it will still be useful as an environmental tracer, since the activity of the $^{99\mathrm{m}}\mathrm{Tc}$ required in this case is much lower than that required for medical examinations (on the order of 10^{-7} times). This is due to the fact that, in environmental studies, the measurement of activity is done with the detector immersed in the sample (the radiotracer occupies all the space around the detector) whereas in medical diagnostics the measurement is done outside the body, covering a small solid angle. It is then possible to use $^{99\mathrm{m}}\mathrm{Tc}$ which is no longer useful in medical clinics as an environmental tracer.

Technetium-99 decays into ruthenium-99 by β^{-} emission, with a very long half-life (211,000 years) and, therefore, very low activity, which will not harm the environment:

$$ {}^{99}_{43}\mathrm{Tc} \rightarrow {}^{99}_{44}\mathrm{Ru} + {}^{0}_{-1}\beta^{-} + \bar{\nu}_{\mathrm{e}} \qquad T_{1/2} = 211 \cdot 10^{3}\ \mathrm{years} $$

After separation of the Mo/Tc mixture, the technetium in the form of $\mathrm{TcO(OH)_2}$ is adsorbed on a sample of the sediment to be studied.

An example of the usefulness of technetium-99m as a sediment tracer is the study carried out at Pampulha Lake, in Belo Horizonte, Brazil. This manmade lake was formed by the building of a dam in the 1950s, to provide flood control, water supply and a new recreational area for the city. The body of water is surrounded by gardens and urban projects designed by renowned architects, landscape artists and urbanists, the ensemble being classified as a World Heritage Site by Unesco. However, the dam faces silting problems, because the sediment brought by the water streams that feed it is deposited in the bottom of the reservoir. The

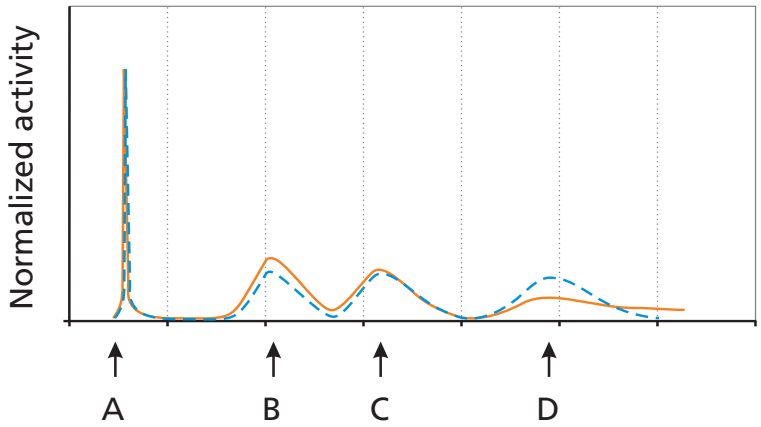
[11] The production of technetium-99m and its use in medicine are described in: R. P. de Carvalho and S. M. Velasques de Oliveira, "Applications of Nuclear Energy in Health", SBPC-IAEA (2017). Available at: <http://portal.sbpcnet.org.br/livro/applicationsofnuclearenergyinhealth.pdf>. Accessed Jan 2019.

[12] The γ energy of the technetium-99m is 3 times lower than that of the gold-198 and, therefore, less care is required in the handling and transport of the material.

normal solution would be to dredge the bottom of the lake and transport the sediments to another area. However, as the region around the dam is now completely urbanized, there is no space available for sediment deposition. The proposed alternative is to deposit the sediment at the outlet of the dam, in order for it to be carried away downstream. This would be the normal pathway of the sediments if the dam did not exist, and this material is needed to support the ecosystem of the watershed because it carries organic compounds necessary for the maintenance of aquatic life.

Consequently, a study was made to determine if the sediments deposited at the outlet of the dam would be transported by the waterways. The tracer used for sediments was technetium-99m, and the water was labelled with Rhodamine WT (Water Tracer). Rhodamine is completely soluble in water and is fluorescent, being easily traced. Figure IV-2 shows this study results.

Figure IV-2: Study of the transport of sediments from the outlet of a dam in Belo Horizonte, Brazil



At point A, Rhodamine (blue dotted curve) and Tc-99m adsorbed in sediments (orange continuous curve) were simultaneously injected. At points B, C and D, water and labelled sediment arrived at the same time. The coincidence in height and shape of the curves shows that the sediment and water move in a similar way. The change in shape of the curves indicates the dispersion of the material in the watercourse; point D is located after a dead zone, where the sediment was dispersed and took longer to pass. Based on: J.V.Bandeira, PhD Thesis - School of Engineering, UFMG (2004). Available at: <http://www.repositorio.cdtn.br:8080/bitstream/123456789/927/1/Tese_JeffersonV_Bandeira.pdf> Accessed Jan 2019.

Tritium as a radioactive tracer in landfills

Tritium (hydrogen isotope containing 1 proton and 2 neutrons) can be used as a radioactive tracer in environmental process studies.[13] It decays into helium-3 (stable) with β^- emission:

$$^{3}_{1}T \rightarrow {}^{3}_{2}He + {}^{0}_{-1}\beta^{-} + \bar{\nu}_e \qquad T_{1/2} = 12.3 \text{ years}$$

The β^- radiation energy emitted is low (6 keV on average) and for its detection it is necessary to use a liquid scintillation detector, which emits light in response to radiation.

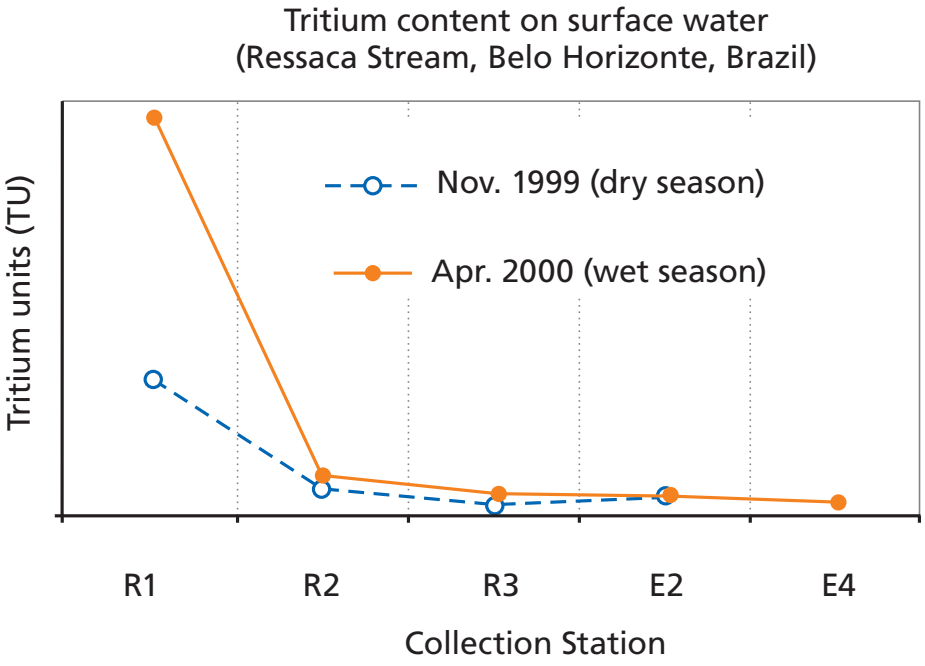
It was found that the concentration of tritium in leachate (liquid exuded by sanitary landfills) is about 10^4 to 10^5 times higher than its concentration in rainwater. The reason for the high concentration has been attributed to the disposal of watch dials, road signs or

[13] The use of tritium as a radiotracer in the oil industry was described in Chapter III: Application of Nuclear Energy in Industry.

luminescent electrical switches in the landfills.[14] The landfill leachate can be harmful to the environment, as it contains microorganisms, high concentration of metals and other pollutants, and can contaminate groundwater. Thus, it is important to trace its pathway, and the high concentration of tritium is an indicator of the leachate presence.

Figure IV-3 shows an example of the use of tritium as a radiotracer of leachate from a landfill.

Figure IV-3: Measurement of the tritium concentration in the vicinity of a sanitary landfill



R1: collection point at the sanitary landfill ; R2, R3, R4: collection points at the watercourse. The reduction in the activity of the tritium indicates that the slurry was diluted in the water course, but is transported by the water, causing pollution. Based on: J. V. Bandeira, PhD thesis - School of Engineering, UFMG (2004). Available at: <http://www.repositorio.cdtn.br:8080/bitstream/123456789/927/1/Tese_JeffersonV_Bandeira.pdf>. Accessed Jan 2019.

Tracer activation

For the analysis of long-term movement of sediments, samples can be labelled with stable elements not present in the region prior to the study. The labelled sediments are released in several positions, with a different tracer being used in each place. At time intervals determined by the dynamics of the process, samples are collected and analyzed by neutron activation to determine the presence and concentration of each tracer, making it possible to determine the direction and speed of the sediment displacement.

For neutron activation analysis, the sample is submitted to a neutron flux in a research reactor. The neutrons are absorbed by the sample nuclei, which emit γ radiation. The energy of this radiation has characteristic values for each element and its intensity is proportional to the concentration of the activated nuclei. Thus, the presence of the element and its concentration in the sample can be recognized.[15]

[14] The reason for the use of tritium in such equipments is that the β emission can be transformed into visible light due to a phosphorescent dye.

[15] Neutron activation analysis is also described in Chapter III - Application of Nuclear Energy in Industry, in the topic: PGNAA.

Radiotracers for soil studies

Soil movement and soil erosion can be studied by determining in the upper soil layers the presence and concentration of natural radionuclides or of the so-called FRN (Fallout Radionuclides). Some of the FRNs are formed in the upper atmosphere by cosmic rays bombardment. Others come from nuclear tests that occurred between the 1940s and 1960s, or from accidents at nuclear power plants, when fission/fusion products spread through the atmosphere across the globe and fell on the Earth's surface.

An example of **natural radionuclide** is potassium-40, which exists in a small proportion in nature.[16] It has two major decay routes, both with the same half-life:

$$^{40}_{19}\mathrm{K} \xrightarrow{90\%} {}^{40}_{20}\mathrm{Ca} + {}^{0}_{-1}\beta^{-} + {}^{0}_{0}\overline{\nu}$$

$$T_{1/2} = 1.3 \cdot 10^{9}\ \text{years}$$

$$^{40}_{19}\mathrm{K} + {}^{0}_{-1}\mathrm{e}^{-} \xrightarrow{10\%} {}^{40}_{18}\mathrm{Ar} + \gamma + {}^{0}_{0}\nu$$

The ^{40}K decay is used for dating rocks, by the determination of ^{40}Ar concentration: in the molten magma material, the argon gas formed by the decay has escaped; after solidification, this gas was trapped in the rock and its concentration, compared to potassium, indicates the time elapsed since the rock formation. The determination of ^{40}Ca concentration is less convenient because calcium may have other origins besides potassium decay. Once the age of the rock is determined, it is possible to infer if there was erosion and sediment transport .

Another example of a **naturally occurring radionuclid**e is beryllium-7. It originates in the upper atmosphere through the collision of atoms of oxygen or nitrogen with protons, coming from the solar wind.[17] ^{7}Be decays into ^{7}Li through electron capture, emitting γ radiation with energy of 480 keV:

$$^{7}_{4}\mathrm{Be} + {}^{0}_{-1}\mathrm{e}^{-} \rightarrow {}^{7}_{3}\mathrm{Li} + \nu + \gamma \qquad T_{1/2} = 53\ \text{days}$$

Because this radionuclide penetrates a maximum of 2 cm in the soil, the determination of the beryllium-7 activity can indicate if there was a recent erosion or soil contribution from another region.

The cesium-137 is a **fallout radionuclide of anthropogenic origin**, coming from uranium-235 fission:

$$^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow ({}^{236}_{92}\mathrm{U}^{*}) \rightarrow {}^{97}_{37}\mathrm{Rb} + {}^{137}_{55}\mathrm{Cs} + 2\,{}^{1}_{0}\mathrm{n}$$

[16] The natural isotopic abundance of ^{40}K is of 0.012%.

[17] This process is called spallation: when the particle strikes on a nucleus, it rips out part of its components in the form of smaller nuclei.

^{137}Cs was released into the atmosphere during nuclear tests or in accidents on fission reactors. Its most likely decay route is:

$$^{137}_{55}Cs \xrightarrow{30\ years} {}^{137m}_{56}Ba + {}^{0}_{-1}\beta^{-} + \bar{\nu} \xrightarrow{153\ s} {}^{137}_{56}Ba + \gamma$$

The γ radiation energy is 0.66 MeV.

In Germany, the topsoil was contaminated with ^{137}Cs from the Chernobyl nuclear power plant accident in 1986. This radioelement is absorbed only by shallow-rooted plants, not deep-rooted trees. The hunting of wild animals, such as deer, is banned during the fall / winter, because during these seasons the animals find no tree leaves and feed on grass and mushrooms. Their flesh is thus contaminated with cesium and should not be consumed. However, since cesium is not metabolized by the animals and is eliminated through their feces, they may be hunted and consumed at other times of the year.

Use of sealed sources

γ *Transmission Analysis*

The transmission of γ radiation depends on the density of the material it crosses. This fact allows the characterization of the sediments suspended in water at ports, dams or navigation channels. Generally, the γ source for transmission measurements is cesium-137, whose production and decay route have been described earlier in this chapter. Its long half-life (30 years) makes it convenient for use in sealed sources.

γ *Backscattering*

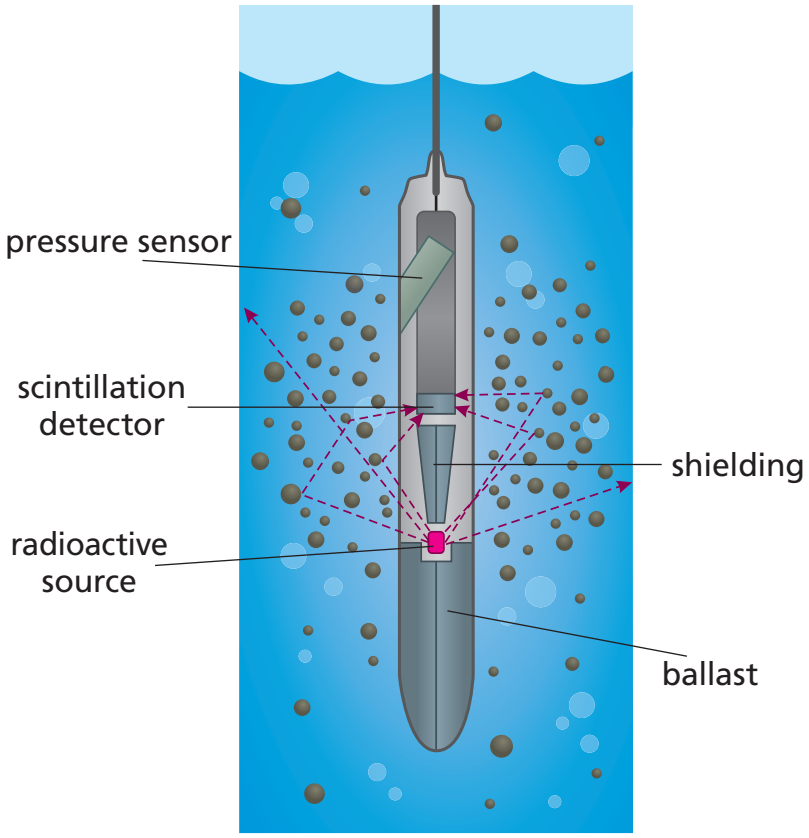
γ analysis can be done even when only one side of the object is available; in this case, source and detector are side by side and one analyzes the γ rays backscattered due to the Compton effect.[18] The intensity of the backscattered beam depends on the density and thickness of the material, and on the scattering angle.

This technique is very useful for the study of sediment concentration in ports, rivers, navigation channels. The analyses can be done at a fixed point, by studying the variation of sediment concentration over time, or by measuring the vertical profile of this concentration.

Figure IV-4 shows the schematic of a backscatter probe.

[18] In the Compton effect, a photon collides with the electron of an atom, behaving like a particle; the exchange of energy between them causes the photon to be scattered with an energy different from the initial one and that depends on the scattering angle. Compton scattering is also described on Chapter I – Fundamentals.

Figure IV-4: Schematic of a γ backscatter probe.



The radioactive source (usually cesium-137) emits in all directions; the radiation that would directly fall on the detector is shielded by a tungsten cone, and only the radiation backscattered by the liquid medium can reach the detector. The ballast at the bottom of the probe allows it to be placed at the desired depth, which can be determined by the pressure sensor. Based on: A. Caillot et. al.: A New Nuclear Density Gauge to Measure Directly High Turbidities in Muddy Areas; available at: <https://icce-ojs-tamu.tdl.org/icce/index.php/icce/article/view/3993/3676>. Accessed Jan 2019.

Meteorological studies

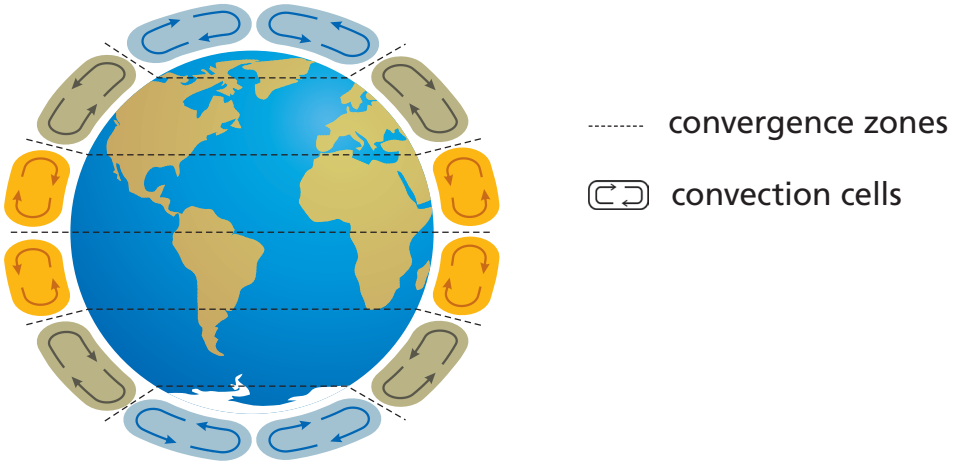
Atmospheric dynamics can be studied using beryllium-7 as a radiotracer. As described earlier in this chapter, this radioelement is formed in the upper atmosphere by spallation of oxygen or nitrogen nuclei; it adheres to aerosol particles[19] which are carried by the wind and fall on the ground due to gravity and rains. The analysis of the presence of ^{7}Be in the lower atmosphere can give information about air movements.

The CTBTO (Comprehensive Nuclear Test Ban Treaty Organization) is a UN organization that monitors worldwide nuclear explosions. It has a global network of detectors that continuously analyze the composition of the air and register the occurrence of seismic events. This network can be used for other studies and researches. The detectors indicate, among other factors, the concentration of ^{7}Be in the atmosphere.

It is known that the terrestrial atmosphere is formed by **convection cells**, where the less dense warm air rises to the upper atmosphere, while cooler, denser air goes down, closer to the ground (Figure IV-5). Regions between two cells are called **convergence zones**. There is a convergence zone near the Equator, two in the temperate zones (one in each hemisphere), and two in the polar regions.

[19] Aerosols are fine particles, solid or liquid, that exist in suspension in a gas.

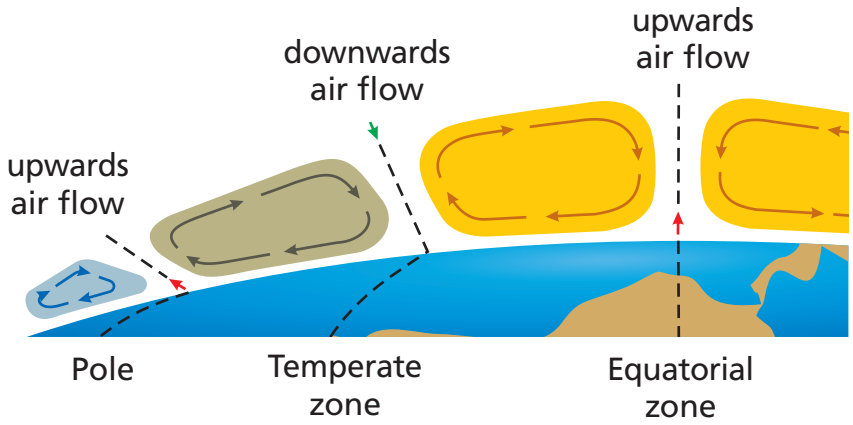
Figure IV-5: Earth's atmospheric convection cells



The region between two cells is called a convergence zone.
Adapted from: L. Terzi, M. Kalinowski, Journal of Environmental Radioactivity 178-179, pg.1-15 (2017), available at: <https://prezi.com/view/t1Daf9pyHDzVF3VD6S1S/>. Accessed Jan 2019.

In the convergence zones at the Equator and at the Poles, the direction of air circulation causes it to rise; in the temperate regions, inversely, we have air that descends (Figure IV-6). As the ^{7}Be is formed in the upper atmosphere, its concentration is expected to be higher in the convergence zone of the temperate regions and lower in the convergence zones of the Equator and the Poles, compared to the concentration in other regions.

Figure IV-6: Circulation of air in the convergence zones

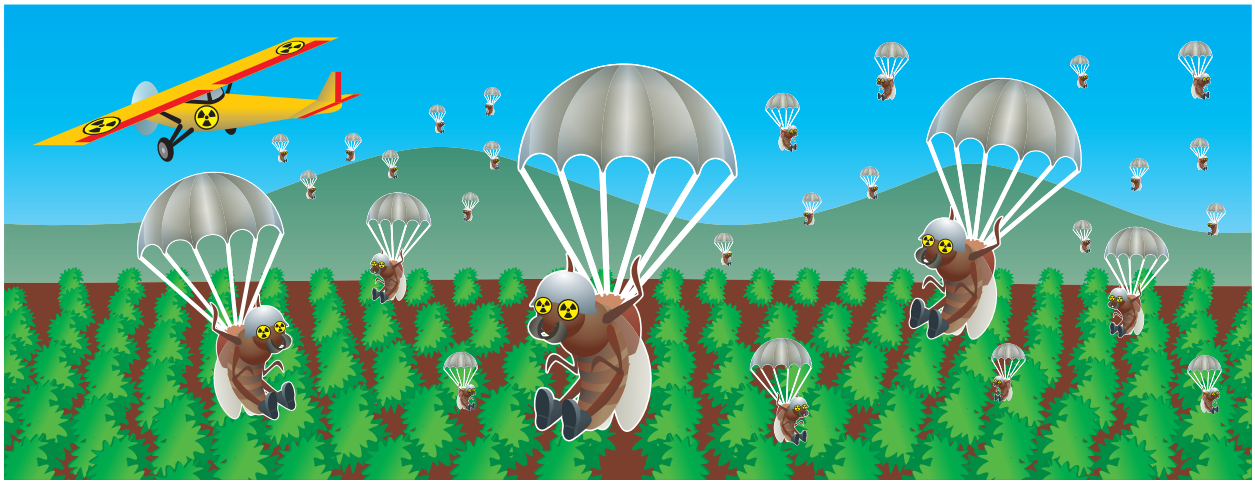


Adapted from: L. Terzi, M. Kalinowski, Journal of Environmental Radioactivity 178-179, pg.1-15 (2017), available at: <https://prezi.com/view/t1Daf9pyHDzVF3VD6S1S/> Accessed Jan 2019.

The convergence zones move slightly north or south, depending on the seasons. By measuring the seasonal variation of the concentration of ^{7}Be, it is possible to determine the position of the convergence zones and their movements and associate the movement with climatic characteristics (summer, winter, rainy or dry seasons, presence and intensity of the *El Niño* phenomenon, occurrence of monsoons, etc).

Acknowledgments: We wish to thank the collaboration of the researchers Rubens Martins Moreira and Jefferson Vianna Bandeira (CNEN, Brazil), João Alberto Osso Júnior, Patrick Brisset and Sabharwal Sunil (IAEA) in the preparation of this chapter.

CHAPTER V - APPLICATIONS OF NUCLEAR ENERGY IN FOOD PRODUCTION



The world's population has grown exponentially, consequently increasing the demand for food. Nuclear energy can be used in the agriculture and livestock industries, enhancing food production: in soil study and preparation, in choosing the best seeds and plant species suited to the climatic conditions, in reducing agricultural pests, in preserving the health of livestock, etc. In this chapter, we will look at some examples of nuclear energy applications.

Soil studies

When preparing a land for farming, it is important to know if the soil is subject to movement or erosion, its humidity, its need for fertilization, among other factors. Nuclear techniques for soil studies include analysis of radiotracer elements or stable isotopes and the use of neutron probes.

Radiotracers, whether natural or of anthropic origin, as well as **stable isotopes** of carbon and nitrogen (^{13}C and ^{15}N), can be used to detect movement of the topsoil, as a sign of erosion or accumulation of material coming from other regions.[20,21]

The isotopic composition of ^{15}N is further used in soil fertilization studies. We know that plants need nitrogen for their development, which is an important element in the formation of chlorophyll. Through measurements of the isotopic composition of ^{15}N in the plant and in the soil, it is possible to determine if the element is absorbed mostly from the soil or from the air. Based on the results of these studies, it is possible to determine if it is desirable to increase the concentration of nitrogen in the soil, either through the use of plants or bacteria that help fix the element, or by artificial fertilization.

[20] The use of radiotracers in the oil industry and in the study of sediment transport was described in Chapters III - Application of Nuclear Energy in Industry and IV - Environmental Studies.

[21] The stable isotopes and the isotopic composition of some elements were detailed in Chapter II - Stable Isotopes.

Neutron probes are used to determine soil moisture, based on the interaction of fast neutrons with water. The source of neutrons used in these probes is an americium / beryllium pellet.[22] Americium-241 is an α emitter:

$$^{241}_{95}\mathrm{Am} \rightarrow {}^{237}_{93}\mathrm{Np} + {}^{4}_{2}\alpha + \gamma \qquad T_{1/2} = 432 \text{ years}$$

Beryllium absorbs an α particle, forming carbon-12 and emitting a fast neutron:

$$^{9}_{4}\mathrm{Be} + {}^{4}_{2}\alpha \rightarrow {}^{12}_{6}\mathrm{C} + {}^{1}_{0}\mathrm{n} + \gamma$$

The energy of the emitted neutrons is on average 4 MeV. The pellets are encapsulated with aluminum, lead or iron to shield the γ emission.

In contact with the earth, the neutron flux collides with the soil elements and exchanges energy with their nuclei. If the masses of the nucleus and the neutron are similar, the exchange of energy is more effective, and the neutrons are thermalized, that is, they have their energy reduced to values of the order of $^{1}/_{2}\,KT$.

Hydrogen, present in water molecules, is the only element with low atomic weight found in significant quantities in typical soils. Thus, the measurement of thermal neutrons is related to the concentration of water in the soil and can determine the amount of artificial irrigation required.

The slow neutron flux is measured, for example, by Geiger-Müller (GM) detectors,[23] using BF_3 gas, with boron enriched with boron-10, which absorbs slow neutrons and emits α particles and γ rays:

$$^{10}_{5}\mathrm{B} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{7}_{3}\mathrm{Li} + {}^{4}_{2}\alpha + \gamma$$

The GM counters determine the intensity but not the energy of the emitted ionizing radiation.

The advantage of measurements made with neutron probes is that they do not depend on the temperature and atmospheric pressure of the site, and are little affected by the salinity, chemical composition of the soil or the type of binding of the water molecules with the soil particles. In addition, the equipment, consisting of the source and the detector, is compact and can be easily transported.

Induced mutation

Mutation is a modification observed in the DNA of a living organism. DNA is a double strand of nucleotides, bound by sugars and phosphates. The nucleotides can have four types of nitrogenous bases: adenine, thymine, cytosine and guanine, identified by the initials A, T, C and G. These bases form A-T or C-G pairs. The functional part of DNA is the gene, which consists of special sequences of hundreds or thousands of A-T or C-G pairs.

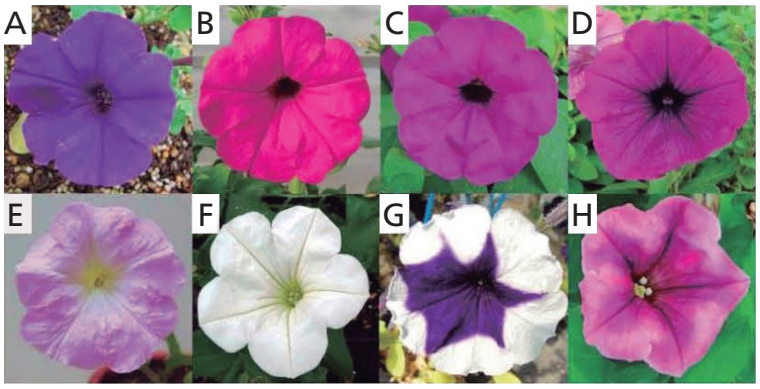
---

[22] The Am/Be source was described on Chapter III - Application of Nuclear Energy in Industry.

[23] The Geiger-Müller detectors were described in Chapter I - Fundamentals.

A mutation can be a point mutation, when there is a single change of nitrogenous base; it can insert or remove bases; or can reverse the order of the bases. The phenomenon was first described by the Dutch botanist Hugo de Vries in the early twentieth century, when he observed mutations in primrose plants. Induced mutation can be done through a chemical treatment (chemical agents) or irradiation (physical agent) of the seeds. The resulting mutations could have happened naturally, however would have taken much longer, perhaps millions of years. Induced mutation can be used to create, for example, plant species which are climate-resistant (drought, saline soil, excessive rainfall, etc.) or more nutritious. Induced mutation in decorative plants may result in flowers with different colors (Figure V-1). The technique, therefore, accelerates the natural evolution of plants. As induced mutations occur at a much higher speed than spontaneous mutations, they increase the likelihood of obtaining desired plant characteristics.

Figure V-1: Flowers of different colors, obtained through ion irradiation of petunia seeds



A: Natural color; B–H: Mutant colors.
Source: Y. Hase et. al.: *Plant Biotechnology* 27, 99–103 (2010)

Rice is an excellent example: in 100 million years, Nature created 140 thousand different rice genotypes;[24] using radiation, it is possible to create new genotypes in less time: from the beginning of the research until results are obtained, the elapsed time is on average 10 years.

Induced mutation is achieved by the exposure of plant seeds or tissues to γ / X radiation, electron or ionic beams.[25] The mutation rate is low (usually between 1% and 10%). After irradiation, the plants are cultivated and those with interesting characteristics are chosen for large-scale reproduction.

Induced mutation was first reported in 1927, using a radon α source.[26] The first applications of induced mutation occurred in 1936 in Indonesia (tobacco), in 1949 in the Netherlands (tulips), in 1950 in Sweden (mustard) and in Germany (beans). Today, the technique is used worldwide to optimize species suitable for feeding people or livestock.

There is a frequent confusion between induced mutation and genetically modified organisms (GMOs). GMOs are obtained by introducing genes from one species in the DNA chain of another species. The studies are recent and there is still no confirmation about the absence of side effects from the consumption of these organisms. On the other hand,

[24] The genotype is the set formed by the genes of an individual.

[25] γ sources are being replaced by X-rays, electron beams or ion beams, as these radiation sources stop emission when they are switched off, while the γ sources emit continuously.

[26] Radon is an α emitter; it belongs to the decay chain of uranium-238:

$$^{222}_{86}\mathrm{Rn} \xrightarrow{3.8\ \text{days}} {}^{218}_{84}\mathrm{Po} + {}^{4}_{2}\alpha$$

induced mutation causes changes in the genes that already exist in the species, silencing some of them and awakening others, thus changing some characteristics of the species. Induced mutation has been used for almost a century, and there are no reports of problems caused by the consumption of food obtained by this technique.

Sterile insect technique

Ionizing radiation may cause mutations, as described in the previous item, or cause some modification in living beings, depending on the irradiation dose. The ability to sterilize insects with radiation is the basis for the application of the **Sterile Insect Technique** (SIT), which aims to develop methods of control or suppression of pests in agriculture, and of insects that cause diseases in humans or animals. The technique has been used for more than 50 years for the control of fruit flies and tsetse flies.[27] Today, it is widely used for the control of agricultural pests (fruit fly, Mediterranean fly), cattle breeding (stable fly, tsetse fly, screwworm fly) and mosquitoes that transmit diseases to humans and animals.

In this technique, a great number of insects are laboratory bred; males and females are separated, usually at the pupa stage, and females are discarded. The male pupae are irradiated with proper doses, resulting in sterile adults that did not lose their mating ability. Sterile insects are released in nature, where they compete with wild males; the females that mate with the irradiated insects do not generate descendants, thus contributing to the control of the population of undesirable insects in the region.

The life cycle of an insect is shown in Figure V-2.

Figure V-2: Life cycle of an insect

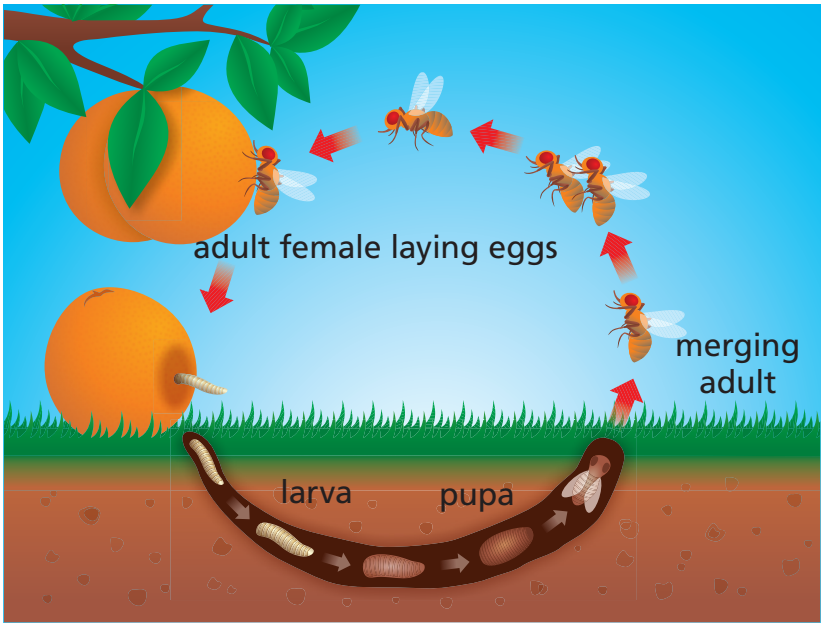


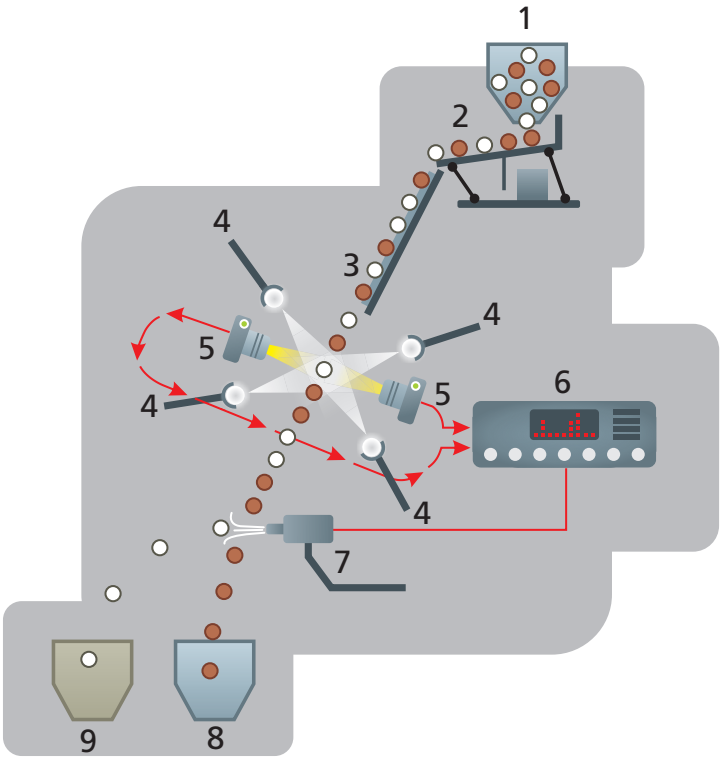
Figure V-3 shows the development of SIT for fruit flies. The male and female pupae have different color (white or black females, depending on the species, and brown males); they can be separated by an optical separator, described in Figure V-4.

[27] The sterile insect technique is also discussed in: R.P.de Carvalho and S.M. Velasques de Oliveira - "Applications of Nuclear Energy in Health" - SBPC, IAEA (2017) - Available at: <http://portal.sbpcnet.org.br/livro/applicationsofnuclearenergyinhealth.pdf>. Accessed Jan 2019.

Figure V-3: Fruit flies bred in captivity

A: The eggs are collected in a container placed under the cage. B: The larvae are bred in trays containing carbohydrates and yeasts. C: Male and female pupae have different colors and can be separated. Photos taken at the IAEA laboratories, Seibersdorf, Austria.

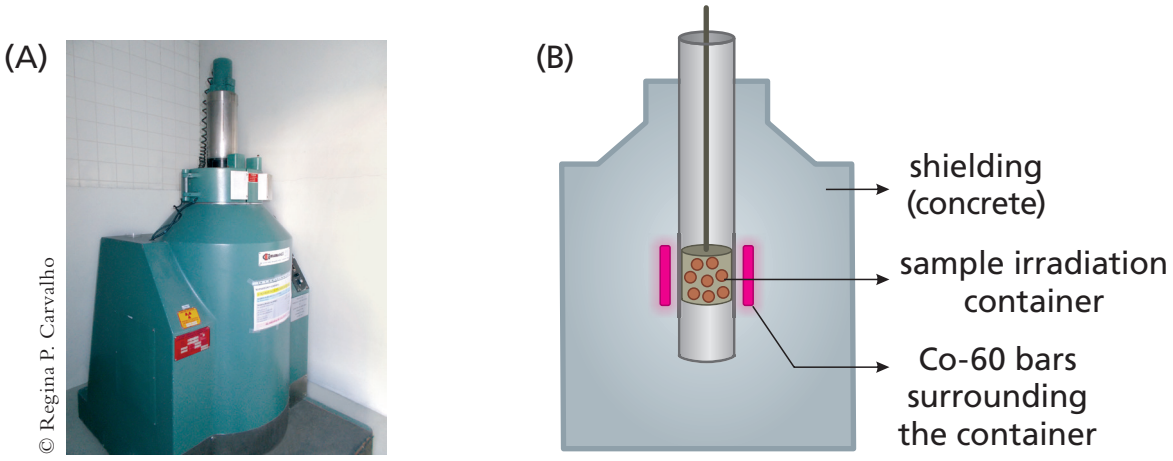
Figure V-4: The process of separating male and female pupae of fruit flies



The pupae are introduced into the separator (1) and a vibrating platform (2) causes the material to fall as a single layer (3). The pupae are illuminated (4) and the image is captured by cameras (5), which send a signal to the processing system (6); this system has previously been programmed to recognize white or dark objects. When a clear (female) pupa is detected, the processor sends an order to a compressed air gun (7), which directs the pupa to the discarded material container (9). Brown pupae (males) are collected separately (8).
Based on a Color Sorter Group document - available at: <http://www.colorsortergroup.com/>. Accessed Jan 2019.

Male pupae are irradiated with cobalt-60, which is γ emitter, into a gammacell (Figure V-5), and incubated. In the research laboratories, after the emergence of the adult males, they are placed in contact with wild insects, in controlled environments that simulate the natural environments (Figure V-6), to verify the interaction between the insects.

Figure V-5: Equipment for γ irradiation (gammacell)



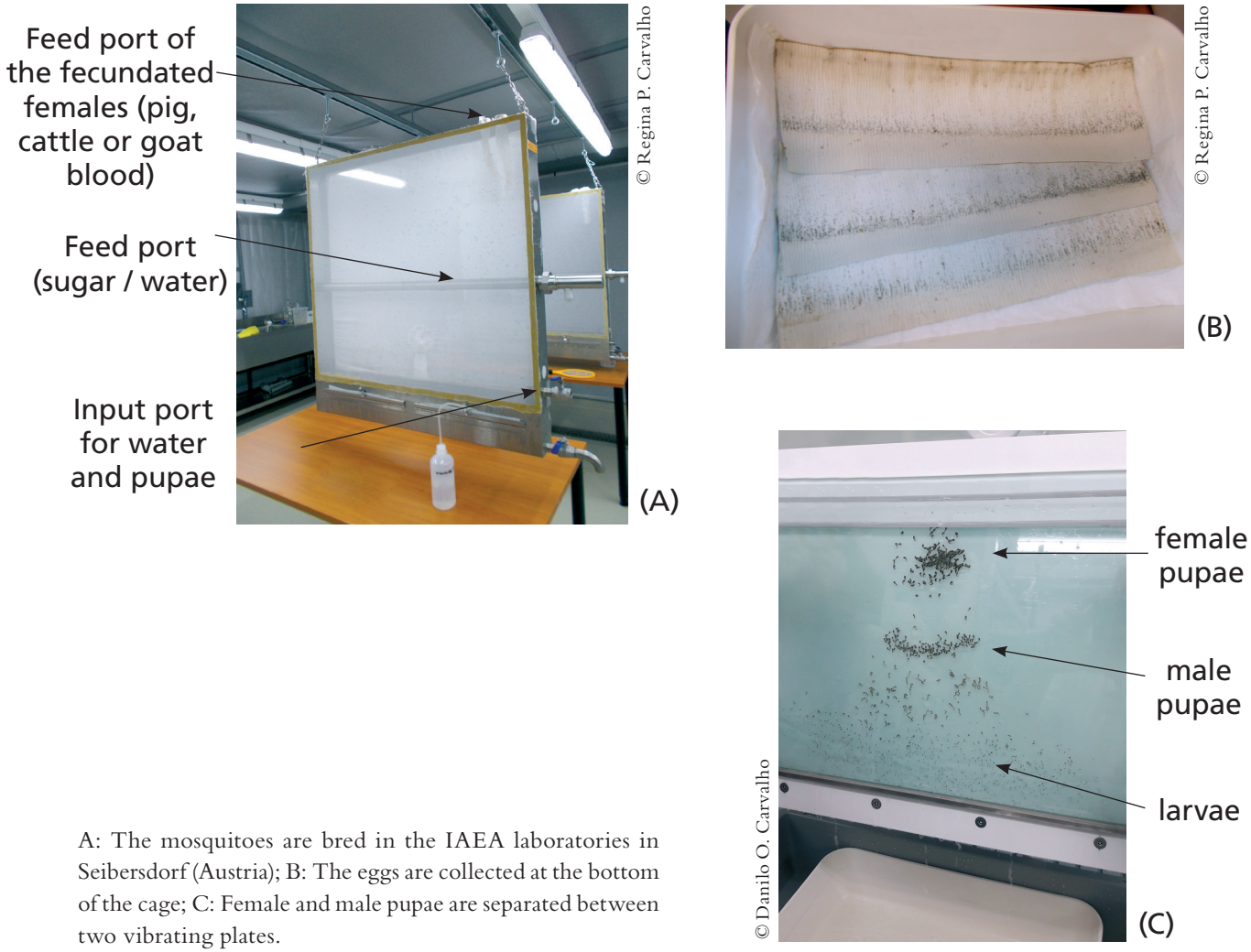
A: External aspect; photo taken at the IAEA laboratories, Seibersdorf, Austria. B: Internal layout.

Figure V-6: Irradiated male insects are placed in contact with wild populations in controlled environments to verify the interaction between them

Photo taken at the IAEA laboratories in Seibersdorf (Austria).

A similar procedure is used for the control of mosquitoes that transmit diseases among humans and animals (Figure V-7). Mosquito male pupae are smaller than female pupae, and can be separated using mechanical methods.

Figure V-7: *Aedes aegypti* breeding



A: The mosquitoes are bred in the IAEA laboratories in Seibersdorf (Austria); B: The eggs are collected at the bottom of the cage; C: Female and male pupae are separated between two vibrating plates.

For other insects, the technique may vary depending on the characteristics of each insect. The separation between males and females of the Mediterranean flies, for example, is done by raising the temperature to 34°C, which kills the female eggs. This mechanism is simpler and more accurate, since it allows the elimination of females in the egg phase, simplifying the insect breeding process.

Other insects are very resistant to radiation sterilization, such as butterflies. However, if the dose is too high, it can kill the insects. On the other hand, if it is too low, it does not sterilize the insect, but will result in sterile offspring in the second or third generation.

The release of sterile adults must be done weekly, in numbers ranging from 15 million to 1 billion insects per week, depending on the type of insect, the area to be covered and the degree of infestation. For use in agricultural areas, batches of insects are cooled to 4°C during transport and stored in a state of latency. The release is done by small airplanes; as they fall, the insects warm up and regain vitality. In urban areas, the release is done on land.

SIT has been quite successful in insect control, and is generally part of a series of techniques used simultaneously; its success depends on involving the whole community in a collaborative effort.

Food irradiation

After growing and harvesting vegetables or obtaining animal products, it is necessary to ensure their conservation during storage and transport, until their delivery to the consumer. The techniques of food irradiation aim at their decontamination, by eliminating bacteria and fungi, controlling pests such as insects, that may become installed in the fruits and seeds, or prolonging their shelf life, inhibiting sprouting. These techniques are applied to grains, herbs, some fruits and vegetables or to meats.

Irradiation can also be performed on prepared meals. This is particularly useful in the case of meals for astronauts, in hospitals or for sending to disaster sites (impacted by earthquakes, floods). In this case, the food is packed with a material that does not deteriorate when subjected to radiation; the packaging prevents the food from coming in contact with microorganisms and being recontaminated. The packaging of irradiated food carries an international logo, named Radura (Figure V-8).

Figure V-8: Radura, the international symbol used to identify food treated with ionizing radiation

Usually, the γ irradiation is carried out with cobalt-60, obtained by bombarding cobalt-59 (stable) in a nuclear reactor:

$$^{59}_{27}\mathrm{Co} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{60}_{27}\mathrm{Co}$$

Cobalt-60 is an energetic γ emitter (1.3 MeV and 1.1 MeV, in equal proportions):

$$^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + {}^{0}_{-1}\beta^{-} + \overline{\nu_e} + \gamma \qquad T_{1/2} = 5.3 \text{ years}$$

However, the use of γ sources brings safety problems in the transport and handling of radioisotopes and is being replaced by X or ion beam irradiation, which only radiate when in operation. The development of new manufacturing technologies is leading to smaller and portable devices.

Livestock

The production of food of animal origin (milk and meat) encounters problems related to parasitic insects such as screwworm fly, cattle fly or tsetse fly and with diseases that affect entire herds, such as hoof-and-mouth disease, rinderpest, swine fever. Control of parasitic insects can be done through the sterile insect technique described earlier in this chapter.

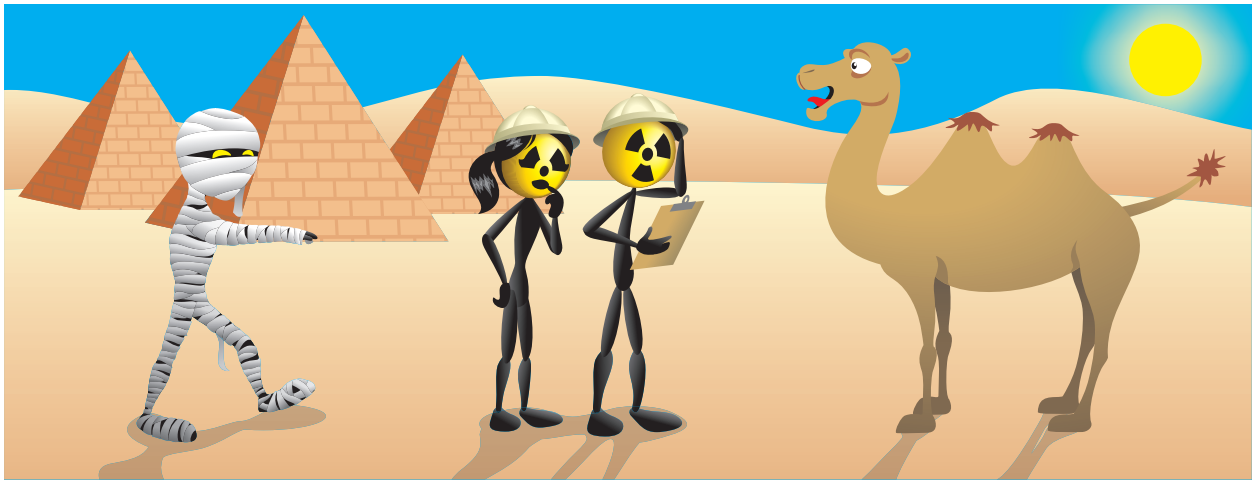
A successful case in SIT application was the eradication of the screwworm flies in North America. This fly lays its eggs in the wounds of the animals, where the larvae feed on their blood and flesh. Infestation in herds leads to a large loss of livestock and a low production of meat or milk.

In 1965, the technique started to be used in Florida, along with other techniques for eliminating insects and educating the population. Over the next 10 years it was extended across all southern states to the west coast of the United States. In 1981, the screwworm fly was considered extinct in the United States, occurring only in isolated cases when pets or racehorses traveled with their owners to Central and South America, where they were contaminated. In each case, a local control was carried out with sterile insects for 6 months.

In 1976 the technique was implemented in Mexico and later extended throughout Central America. Since 2000 there has been a sanitary barrier in the Panama Canal, with weekly release of sterile insects, to avoid recontamination by insects coming from South America.

Acknowledgments: We wish to thank Carlos E. Caceres, Danilo O. Carvalho, Jorge Hendrichs, Carl M. Blackburn, Zhihua Ye and Fatma Sarsu (IAEA) and Antonio Costa de Oliveira (Univ. Federal de Pelotas, Brazil) in the preparation of this chapter.

CHAPTER VI – STUDY AND PRESERVATION OF CULTURAL HERITAGE



Nuclear techniques are useful tools in the preservation and study of tangible cultural heritage. For example, γ irradiation can be used to kill fungi, microorganisms or insects in books and ancient works of art. The applied dose can be calculated to eliminate unwanted organisms without affecting the material to be preserved.

The composition of inks, ceramics or metal alloys used in past eras can be revealed using the neutron or γ-ray analysis techniques described in Chapter III - Application of Nuclear Energy in Industry.

Gammagraphy, also described in the same chapter, is used to show the interior of statues and other works of art.

In addition to these, the carbon-14 dating technique is used to learn the age of fossils; and a new technique of non-destructive analysis was recently proposed for the study of large ancient buildings: the muography.

Dating with carbon-14

^{14}C is formed in the upper atmosphere by the bombardment of nitrogen-14 by cosmic rays:

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

^{14}C is absorbed by living organisms as CO_2, in the same way as the stable isotopes ^{12}C and ^{13}C. It is unstable, and transforms into ^{14}N by β^-decay :

$$^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}\beta^- + \bar{\nu} \qquad T_{1/2} = 5{,}730 \text{ years}$$

The carbon-14 isotopic ratio is constant as long as the organism is alive (on the order of 10^{12} atoms of ^{12}C for every ^{14}C atom), but it decreases after death, as ^{14}C decays into ^{14}N and there is no further absorption. Thus, by determining the $^{14}C/^{12}C$ ratio, it is possible to infer how long ago the organism died. In general, the assumption is that the isotopic carbon ratio in the atmosphere did not vary over time.

The earliest radiocarbon dating was done in the 1940s, by counting the β^- emissions of the ^{14}C. However, due to the small proportion of this isotope in a carbon sample, large amounts of material and long counting times are required. For example, a sample of 1 g of "present" carbon has on average 15 emissions per minute; in order to obtain accurate information, it would be necessary to count for at least 12 hours. For old samples in which part of the ^{14}C has already decayed, counting may take weeks or months.

Currently, the mass spectroscopy technique described in Chapter II - Stable Isotopes can be used to determine the ratio of ^{14}C in the total carbon of a sample. The analysis can be done quickly (10 to 30 minutes), and very small samples are used ($\sim$ 0.1 mg), which reduces the damage caused to the piece studied.

Carbon-14 can therefore be used to determine the age of any old object containing carbon of organic origin, such as bones of humans or animals, shells, food remains in prehistoric vessels, paper, cloth, straw, material of plant origin found in old bricks etc.

Muography

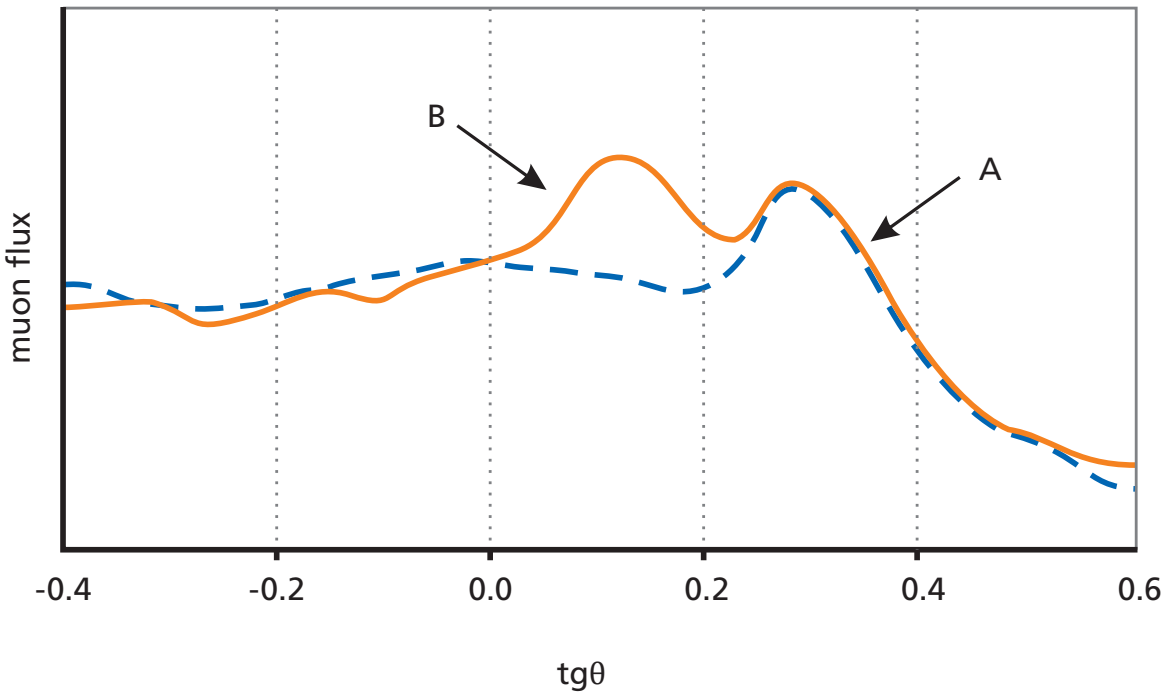
Muons (pronounced 'mee-ons') are negative particles, similar to electrons, but with a mass about 200 times greater than that of the electron. They are formed in the upper Earth atmosphere by collisions between the cosmic rays and the molecules of the atmosphere. Muons interact very little with matter and reach the Earth's surface with high energies. When traversing large volumes, they lose energy proportionally to the density of the material and the distance traversed.

Due to the fact that the flow of muons is intense across the surface of the globe, they can be used to examine the interior of large structures (mountains, large buildings, etc.). Muography is similar to γ scanning or radiography, with the advantage that the radioactive source exists permanently anywhere on Earth. Detection of muons is done by emulsion films, and can be confirmed with scintillation detectors.

An example of application of muography is the study of the interior of the Vesuvius volcano. Through the obtained images, one can observe the formation of pockets of lava and infer the occurrence of future eruptions.

In another recent study, the structure of the interior of the pyramid of Khufu, Egypt, was investigated. From the measurements, it was possible to determine the existence of an empty space, until now unknown, inside the pyramid (Figure VI-1).

Figure VI-1: Flow of incident muons, as a function of the position of the detectors, in the Khufu pyramid (Egypt)



The orange continuous curve shows the experimental data. The blue dotted line shows the expected flow, taking into account the known structure of the pyramid. The increase in flow in region A is due to the presence of a known tunnel (absence of material that could attenuate the flow). Region B presents an unexpectedly high value for the flow, indicating the existence of a void, hitherto unknown.
Based on: K. Morishima et. al.: NATURE , 552 (21/28), 386 (2017).

Some companies are currently proposing the use of muography to verify the cargo transported in closed trucks.

READING SUGGESTIONS

The concepts of Nuclear Physics and its applications, discussed in this book, can be found in basic reference books, such as:

BRIMICOMBE, Michael W. **Physics in Focus**. Melbourne: Nelson Thornes Ltd., 1990.

HALLIDAY, David; RESNICK, Robert; WALKER, Jearl. **Fundamentals of Physics**. 10th ed. New York: John Wiley & Sons, Inc., 2014. v.2.

HEWITT, Paul. **Conceptual Physics**. 12th ed. Boston: Pearson Education, Ltd., 2015.

JONES, Edwin R.: CHILDERS, Richard L. **Contemporary College Physics**. 3d ed. New York: McGraw-Hill, Inc., 2000.

SERWAY, Raymond A.; JEWETT, John W. **Physics for Scientists and Engineers with Modern Physics**. 8th ed. Belmont: Brookscole, 2009.

Some websites offer information on nuclear power and its applications:

The Periodic Table. Available at: <http://periodictable.com/index.html>. Accessed Jan 2019.

NUCLEAR SCIENCE WALL CHART. **Guide to the Nuclear Wall Chart**. Available at: <http://www2.lbl.gov/abc/wallchart/guide.html>. Accessed Jan 2019.

Radioactivity and its applications – IN2P3, France. Available at: <http://www.radioactivity.eu.com/>. Accessed Jan 2019.

Radiotracer Applications in Industry – A Guidebook - IAEA, Vienna, 2004 – Available at: < https://www-pub.iaea.org/MTCD/Publications/PDF/TRS423_web.pdf>. Accessed Jan 2019.

Use of Radiotracers to Study Surface Water Processes - IAEA-TECDOC-1760, Vienna, 2015. Available at: <https://www-pub.iaea.org/MTCD/Publications/PDF/TE-1760_web.pdf>. Accessed Jan 2019.

Fundamentals of stable isotopes geochemistry – Carol Kendall, USGS (2010). Available at: <https://wwwrcamnl.wr.usgs.gov/isoig/res/funda.html>. Accessed Jan 2019.

Regina Pinto de Carvalho is a retired professor and researcher of the department of Physics at the Universidade Federal de Minas Gerais [UFMG], Brazil, where she has always sought to promote the teaching of Physics at all levels, through advising students or training future teachers and professors. She remains dedicated to this goal, both inside and outside the University, and continues training teachers while also producing texts and books to make the study of Physics more accessible and captivating. Regina was born in Belo Horizonte, in 1950, where she currently lives, after having worked and studied in other cities in Brazil and abroad. She has two children and three grandchildren.

"The book is actually very well written, concise and easy to read! ...
I think it's great that [the author] is spreading awareness for everyone,
especially when people is scared about [nuclear energy] nowadays.
I think it's a good book to have in the classroom."
(Gauri, engineering student)

"[The text is] very entertaining to read and certainly will help
non-experts to see nuclear and isotope techniques
with a new, more positive perspective."
(L. Araguas, Geochemistry researcher)

"It is very important to explain [the nuclear applications]
in an easy to understand way to the wider public."
(J. Hendricks, Biology researcher)

IAEA
International Atomic Energy Agency
Atoms for Peace

SBPC Sociedade Brasileira para o Progresso da Ciência

SBF
SOCIEDADE BRASILEIRA DE FÍSICA

CDTN
CENTRO DE DESENVOLVIMENTO DA TECNOLOGIA NUCLEAR

CNEN
Comissão Nacional de Energia Nuclear

MINISTÉRIO DA
CIÊNCIA, TECNOLOGIA, INOVAÇÕES E COMUNICAÇÕES
GOVERNO FEDERAL - BRASIL