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SBPC Sociedade Brasileira para o Progresso da Ciência

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This book is addressed to high school students and teachers, with the intent of providing consistent information about Nuclear Physics that meet the classroom needs.

Nuclear Physics studies the phenomena that allow the peaceful and beneficial use of nuclear energy. There are several important applications of radioisotopes, natural or artificially produced in dedicated accelerators or reactors, such as in diagnosis or therapy, agriculture or the environment, as well as in industry and in energy generation.

This book describes the basic characteristics of the atomic nucleus and its potential transformations, the main radioisotopes currently used in practical applications and the operation of the main types of radiation detectors, which permit the identification of the presence of exposure to ionizing radiation in humans or the environment. Some questions are proposed for research and classroom discussion, as well as simple activities that illustrate basic concepts.

To the extent possible, the illustrations in the book have been designed for readability by color-blind people. However, if the reader has any problem interpreting any figures, please contact us so we can improve upon the presentation.

We would like to thank the many people in Brazil who assisted in the development of the content through their contributions and comments: Professors Edvane Borges (*Universidade Federal de Pernambuco*), Hérika Vasconcelos, Napoleão Ramalho, Orlando Aguiar and his students (*Universidade Federal de Minas Gerais*), Ana Márcia G. Sousa and her students (*Faculdade Pitágoras*), Juliana Batista da Silva, Carlos Malamut, Andréa Vidal, Thessa C. Alonso and their team, Wilson Calvo (*Comissão Nacional de Energia Nuclear*). We also thank João Alberto Osso Junior (International Atomic Energy Agency - IAEA) and Ms. Marcia Clarke (Vienna International School, Austria).

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Silvia and Regina
April/2017

I – INTRODUCTION TO THE ATOMIC NUCLEUS

Until the end of the nineteenth century, the atom was described by means of a simplified model, based on observations of the behavior of materials. According to this model, the negative electrons move around positive nuclei, which are supposedly composed of protons, positive particles with a mass approximately 2,000 times greater than the mass of the electrons. Discoveries made by scientists in the late nineteenth and early twentieth centuries led to changes in this simplified model. Today, it is believed that the atom has a positive nucleus and negative electrons, located in the region surrounding the nucleus. The volume of the atom is determined by the so-called electronic cloud (region where the electrons are located),[1] and its mass is mainly related to the mass of the nucleus.

The composition of the nucleus

The earliest information regarding the atomic nucleus, at the end of the nineteenth century, came from the discovery of radioactivity by French physicist Henri Becquerel (1852-1908) and subsequent studies by Polish chemist Marie Curie (1867-1934), aided by her husband, the French physicist Pierre Curie (1859-1906).[2] Emissions from the nucleus were called α particles (Greek letter, alpha), β (Greek letter, beta) or γ (Greek letter, gamma), based on their ability to penetrate matter (FIGURE I-1). The energies involved in these emissions are in the order of MeV (millions of electron-volt).[3]

The concept that the nucleus was composed only of positive particles was flawed, since particles of the same charge repelled each other and caused instability of the nucleus. The discovery of the neutron, in 1932, by English physicist James Chadwick (1891-1974), led to yet another change in the model for the nucleus. The neutron is a particle with a mass similar to that of the proton but with no electric charge. There are forces of attraction, called

[1] The radius of an atom is on average 10^4 times greater than its nucleus: if the nucleus had a radius equal to a dot made by a pen (~1 mm), the atom would have the size of a classroom (~10 m).

[2] Pierre Curie was carrying out research on magnetism, and his wife, Marie Sklodowska Curie, was researching the emissions of certain atoms, which she called radioactivity. Realizing the importance of Marie's work, Pierre decided to help her and postponed his studies on magnetic materials, which were left unfinished due to his early death.

[3] $1 MeV = 10^6 eV = 1.6 \cdot 10^{-13} J$

nuclear forces, between the nucleons, these being the particles that make up the nucleus (protons and neutrons). Thus, the nuclear attraction forces between the nucleons compensate for the electrostatic repulsion between the protons, and it is possible to have stable nuclei, when there is a number of neutrons equal to or greater than that of protons.

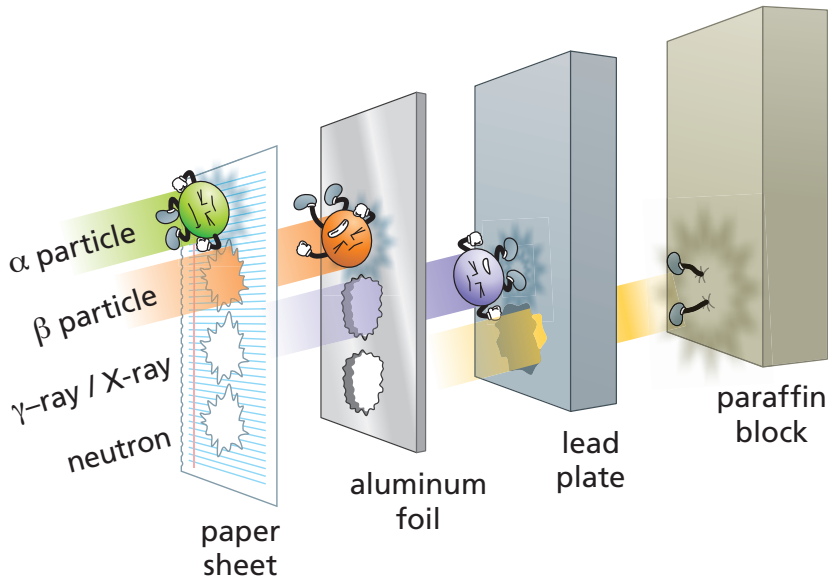
Nuclear forces are stronger than electromagnetic and gravitational forces, but have a very short range. Therefore, it is not possible to have very large stable nuclei: the nuclear attraction acts only between neighboring nuclei, whereas the electrostatic repulsion acts on all protons, regardless of the distance between them.

It is now known that α particles are composed of 2 protons and 2 neutrons and are similar to he nucleus of the element helium; the β particles are identical to the electrons, and the γ particles are high energy photons (TABLE I-1). Neutrons and protons exist permanently within the nucleus; the β particles are created during the emission process.

Table I-1 – Characteristics of nuclear particles

Particle	Composition	Blocked by
α	2 protons and 2 neutrons	paper sheet
β	electron	aluminum foil
γ	high energy photon	lead plate or a concrete block several meters thick
n	neutron	boron or paraffin block

Figure I-1 – Materials that can shield the particles



Other particles can also be emitted from a nucleus, such as positrons, that have the same mass as the electrons, but containing a positive charge, described by the symbol β^+ (beta-*plus*), or neutrinos, which have a much smaller mass than that of the electrons and carry no charge, described by the symbol ν (Greek letter, nu) or $\bar{\nu}$ (nu-bar), in the case of antineutrinos. The neutrinos carry momentum and energy, being responsible for the conservation of these quantities during nuclear transformations.

Nuclear reactions

After the spontaneous emission of α, β or γ particles, a nucleus will have its composition modified. This emission is called radioactive decay.

The emission of an α particle decreases the number of protons by 2 and also the number of neutrons of the nucleus by 2; then this nucleus becomes another one, with its charge reduced by 2 units, and its mass decreased by 4 units.

A β emission decreases the charge of the nucleus by 1 negative charge, that is, it increases the charge of the nucleus by 1 positive unit, leaving the total mass of the nucleus unchanged. This is equivalent to transforming a neutron into a proton. This emission will always be associated with the emission of an antineutrino $\bar{\nu}$, which carries energy and momentum without changing the charge or the mass of the nucleus.

In β^+ emission, 1 positive charge is withdrawn from the nucleus, and its mass is not changed; this is equivalent to transforming a proton into a neutron. This emission is always associated with the emission of a ν neutrino, which allows the conservation of energy and momentum.

The γ emission removes the excess energy from the nucleus. Its function is to bring to the ground state a nucleus that was in a higher energy state (represented by an asterisk – as an exponent - after the symbol of the element), after the emissions of particles.

Nuclear emissions can be represented similarly to chemical reactions: each nucleus is represented by the chemical symbol of the element to which it corresponds; a number on the left, below the symbol, represents the number of protons in that nucleus;[4] while a number on the left above the symbol represents the mass number of the nucleus (number of protons + number of neutrons).

Below we can see some examples of nuclear emissions or reactions. In these equations the symbol n is used for neutrons, or, in some cases, ${}_0^1\mathrm{n}$. Protons, which are hydrogen nuclei, are represented by p, ${}_1^1\mathrm{p}$ or by ${}_1^1\mathrm{H}$; for the deuterium, which is a hydrogen nucleus with 2 nucleons (1 proton and 1 neutron), we use the symbols d, ${}_1^2\mathrm{d}$ or ${}_1^2\mathrm{H}$. Tritium (hydrogen nucleus with 3 nucleons, i.e., 1 proton and 2 neutrons) is represented as ${}_1^3\mathrm{H}$.

The α, β and γ decays may be shown as follows:

$$
\begin{aligned}
{}_{94}^{238}Pu &\rightarrow {}_{92}^{234}U + {}_{2}^{4}\alpha \\
{}_{92}^{234}U^{*} &\rightarrow {}_{92}^{234}U + \gamma \\
{}_{6}^{14}C &\rightarrow {}_{7}^{14}N + {}_{-1}\beta + \bar{\nu}
\end{aligned}
$$

Nuclear emissions bring the nucleus to its ground state (lowest energy state). Normally, very large nuclei are unstable; when they emit particles, they are transformed into a different chemical element (when the number of protons is changed) or isotopes of the same element (when only the number of neutrons is changed).[5] When an unstable nucleus emits photons, it releases the excess energy and approaches its ground state.

A nucleus can also be artificially modified if it is bombarded by particles, photons or other nuclei. This leads to a nuclear reaction in which the nucleus can be transformed into an isotope of the same element or into another element; or it can break into two or more

[4] It is not necessary to specify the number of protons, since this is determined by the symbol of the element; however, it may be useful to display this number to facilitate visualization of the nuclear process.

[5] Isotopes are nuclei that differ in the number of neutrons, but have the same number of protons. They therefore correspond to the same chemical element, but have different masses.

smaller nuclei or merge with another nucleus, forming a larger nucleus. In all these cases, there may be an emission of particles or photons, and the nuclei and particles resulting from the reaction carry kinetic energy: there is always conservation of mass/energy and of momentum.[6]

The following are some examples of nuclear reactions:

$$
\begin{gathered}
{}_0^1n + {}_{92}^{235}U \rightarrow ({}_{92}^{236}U^*) \rightarrow {}_{56}^{141}Ba + {}_{36}^{92}Kr + 3{}_0^1n + E \\
{}_1^2H + {}_1^3H \rightarrow {}_2^4He + {}_0^1n + E \\
{}_7^{14}N + {}_1^1p \rightarrow {}_6^{11}C + {}_2^4\alpha + E \\
{}_{25}^{55}Mn + {}_1^2H \rightarrow {}_{26}^{55}Fe + 2{}_0^1n + E \\
{}_8^{18}O + {}_1^1p \rightarrow {}_9^{18}F + {}_0^1n + E
\end{gathered}
$$

Nuclear reactions can also be represented by indicating the initial nucleus, the particles involved in parentheses, and the final nucleus. Thus, the last three reactions shown above can be also represented as follows:

$$
\begin{gathered}
{}^{14}N\,(p,\alpha)\,{}^{11}C \\
{}^{55}Mn\,(d,2n)\,{}^{55}Fe \\
{}^{18}O\,(p,n)\,{}^{18}F
\end{gathered}
$$

Conservation of mass during a nuclear reaction

The mass of a nucleus is not equal to the sum of the masses of the protons and neutrons that compose it. During the merging of these particles in the formation of a new nucleus, there may occur a release of energy, thus decreasing the total mass. Conversely, in order to separate the nucleus into its constituent particles, it may be necessary to provide energy to the system. This energy, called the nucleus bonding energy, is given by the Einstein equation, which relates mass (**m**) and energy (**E**):

$$E = \Delta m \cdot c^2$$

where **c** is constant and equal to the speed of light:

$$c = 3 \cdot 10^8 \text{ m/s}.$$

In nuclear reactions, the sum of the masses of the initial products may be different from the sum of the masses of the final products, and the balance appears as energy supplied by or released in the system.

The most significant examples of the equivalence between mass and energy are the so-called pair production, and the inverse phenomenon, the pair annihilation.

---

[6] As we shall see below, mass can be transformed into energy, and vice versa.

The production of an electron-positron pair can occur with the energy delivered by a photon, provided that it has enough energy. This must happen in the vicinity of a nucleus, which recoils, in order to preserve momentum.

In the inverse phenomenon, an electron and a positron are annihilated, and two photons of equal energy are created (0.511 MeV each). The sum of the energies of the two photons is equivalent to the added masses of the electron and the positron, and the direction of the emission of the photons can be determined using the law of momentum conservation.

Radioactive decay

In an atom, the nucleus is surrounded by electrons and therefore does not suffer the influence of temperature, pressure, or any other external factor. The transformations that occur within the nucleus, such as radioactive decay, depend solely on its internal conditions.

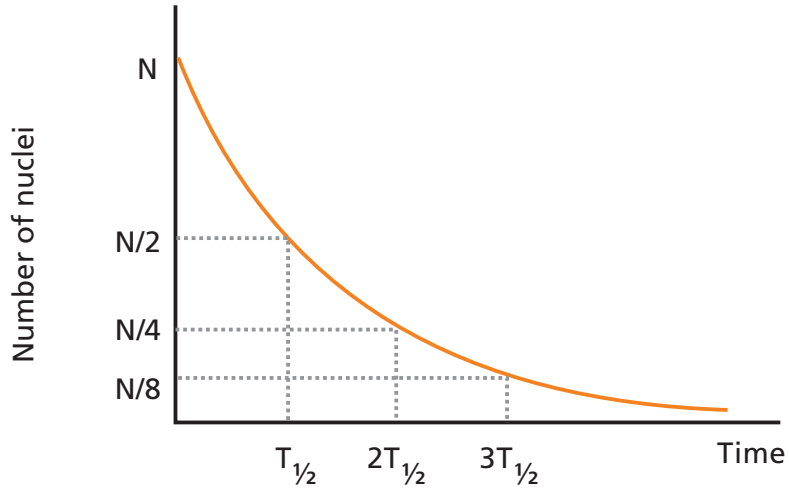
During radioactive decay, the number N of radioactive nuclei (nuclei capable of emitting particles) decreases with time t, according to an exponential law:

$$N = N_0 e^{-\lambda t},$$

where N_0 is the initial number of radioactive nuclei, and λ is a constant that depends on the specific type of decay.

The time required for the decay of half the nuclei in a given sample is called the half-life $T_{½}$. Thus, if at the beginning of an observation there are N radioactive nuclei in a certain sample, after a half-life has elapsed, we will have $\frac{N}{2}$ radioactive nuclei; after 2 half-lives, we will have $\frac{1}{2} \cdot \frac{N}{2} = \frac{N}{4}$ radioactive nuclei, and so on. Figure I-2 shows the variation in the number of radioactive nuclei as a function of time.

Figure I-2 – Variation in the number of radioactive nuclei as a function of time



The half-life of radioactive elements can range from very large quantities (millions of years) to very small ones (thousandths of seconds). See Table I-2 for some half-life values.

Table I-2 – Half-life of some elements

Name of element	Symbol	Half-life
Uranium-238	^{238}U	4.5 million years
Radium-226	^{226}Ra	1,600 years
Cesium-137	^{137}Cs	30.2 years
Iodine-131	^{131}I	8.0 days
Metastable Technetium-99	^{99m}Tc	6.0 h
Iodine-128	^{128}I	25 min
Silver-110	^{110}Ag	24.6 s
Radon-217	^{217}Rn	1 ms

Source: MEYERHOF, W. E. **Elements of Nuclear Physics** – New York: McGraw-Hill, 1967.

Only elements with a half-life greater than the Earth's age are found in nature, because all others have already decayed since their formation. Therefore, we can speak of **natural radioactivity** (radioactive elements found in nature) and **induced radioactivity** or artificial sources of radiation (elements that have undergone transformations achieved in a laboratory and become radioactive). In some regions, radioactive elements buried underground rise to the surface, due to human actions such as mining, modifying the natural radioactivity of the site.[7] We can also find radioactive elements formed through bombardment by cosmic rays in the upper atmosphere, which then reach the Earth's surface.

The half-life value $T_{½}$ for each nucleus depends on its internal constitution, which is the subject of Particle Physics studies.

The half-life concept is also used in other areas to describe any value that decreases exponentially with time. When there are different uses of this concept in the same text, the half-life related to radioactive decay is called **physical half-life**,[8] in order to distinguish it from the others. In particular, in Pharmacology, the **biological half-life** of a drug is defined as the time required for half of the dose administered to a living being to be eliminated from the body through the renal, gastric, respiratory, etc. systems. The combination of the physical half-life of the radioisotope with biological half-life (which depends on biodistribution) is called the **effective half-life**.

Why is the knowledge of physical half-life important in medicine?

The physical half-life is one of the important parameters for planning a medical procedure.

In radioisotope applications for diagnostic or therapeutic purposes, a distinction should be made when the exposure is external (e.g. sealed sources for brachytherapy) or internal (e.g. radiopharmaceuticals for imaging or therapy, when the sources are incorporated). In the case of sealed sources for brachytherapy, treatment planning takes into consideration, among other factors, the physical half-life of each element. Regarding radiopharmaceuticals, the issue is more complex, since the biological half-life, which depends on the biodistribution

[7] This phenomenon is called NORM (Natural Occurrence of Radioactive Materials).

[8] In this book, where there is no ambiguity, the physical half-life will be called simply half-life.

of the material inside the body, must also be taken into account. In this book, we will not go into greater detail regarding biological half-life.

When a radiopharmaceutical is used for diagnosis, its physical half-life must be compatible with the time of the image acquisition (maximum 20-30 min). However, this precaution of time limit would be of no use if the image were obtained before the maximum point of the radiopharmaceutical biodistribution in the body, in order to obtain the best possible image. The technicians who carry out the procedure have professional training and carefully calculate all the parameters for a good image acquisition. After the material has been excreted by the patient, special care concerning radiological protection is provided by professionals specialized in radioactive waste management.

Nuclear fission

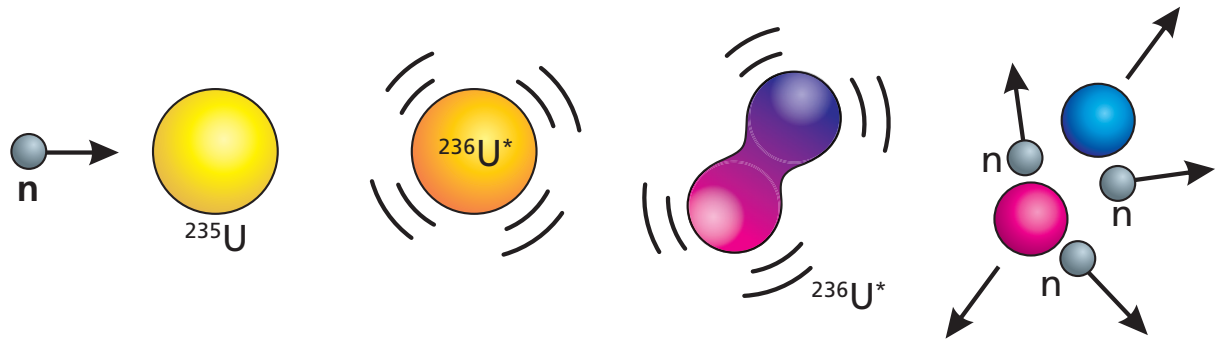
One of the most interesting examples of nuclear reaction is **fission**: it occurs when a nucleus splits into two, usually due to external interference. Uranium-235, for example, as it captures a neutron, is divided into two nuclei, each one having about half of the total mass. During fission, other neutrons and a large amount of energy are released. A typical example of fission is given by the reaction:

$$n + {}^{235}_{92}U \rightarrow ({}^{236}_{92}U^{*}) \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3n + E$$
$$E = 175\ MeV$$

The energy released corresponds to the difference in mass between the initial and the final components of the reaction. Although this is the most likely reaction for the ^{235}U, there are other possibilities with other fission products.

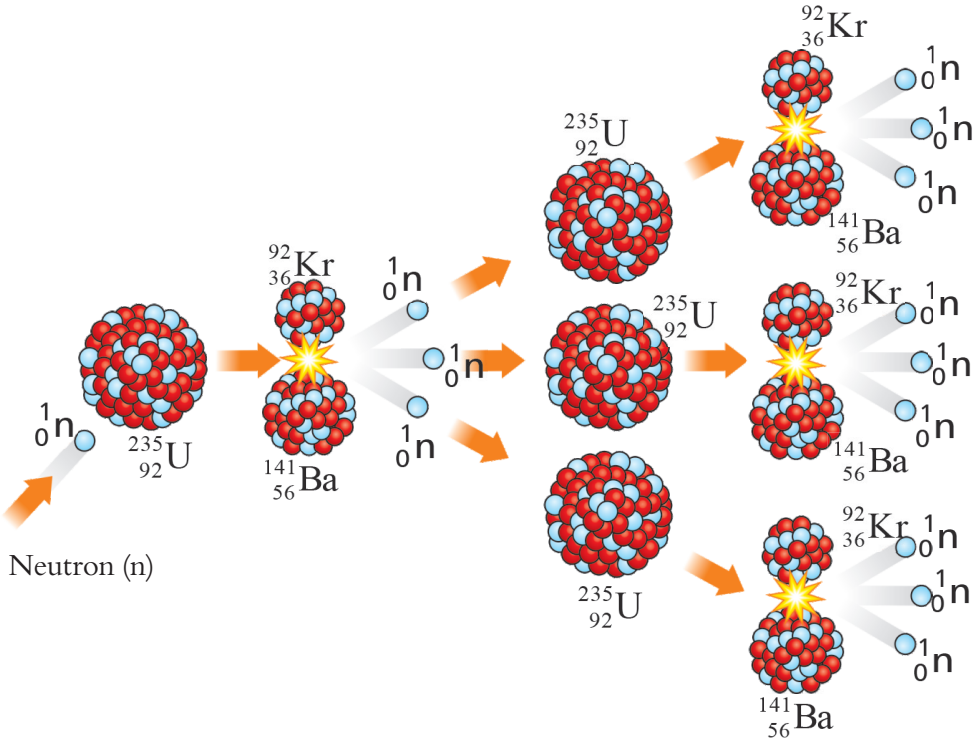
Figure I-3 shows a nuclear fission sketch.

Figure I-3 – A nuclear fission sketch



During the fission of the ^{235}U, each nucleus divides into two others and releases a certain amount of energy, in addition to 3 neutrons. If each neutron reaches another nucleus, we will have the fission of 3 nuclei, providing 3×3 neutrons and three times the initial energy amount, and so on. The number of neutrons and the energy released increases. We call such a reaction a **chain reaction** (FIGURE I-4).

Figure I-4 – Chain reaction in nuclear fission



It is possible to control the fission reaction, in order to use, in each reaction, only one neutron for a new fission; this is what takes place in a nuclear reactor, where the fissile material is surrounded by absorbers in the proper positions and quantities. In this case, the energy released is always constant.[9]

The ^{235}U fission energy is used in power reactors for heating water, producing steam to move turbines to generate electricity. In other types of reactors (multi-purpose reactors), the neutrons released in fission reactions are used for research or for radioisotope production.

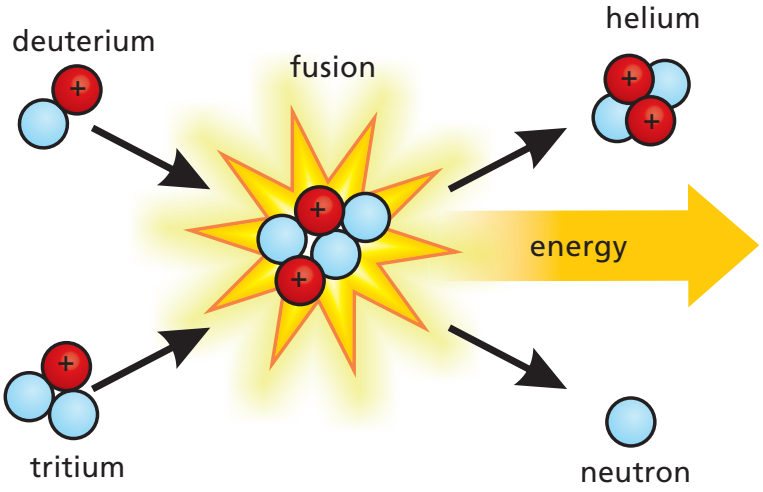
Nuclear fusion

Another example of a nuclear reaction is **fusion**, which occurs when two light nuclei combine to form one heavier nucleus. An example is the fusion of a deuterium ($^{2}_{1}H$) and a tritium ($^{3}_{1}H$) in helium, with the emission of a neutron and a certain amount of energy (FIGURE I -5):

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

[9] If more than one neutron is used in each reaction, the released energy will increase exponentially from one stage to the next and can cause great damage. When the fissile material is used in large proportions and purposely more than one neutron from each reaction is saved for the next step, a lethal weapon is obtained. There is currently an international agreement not to use this type of weapon.

Figure I-5 - Sketch of the fusion reaction



Since the sum of the initial masses is greater than that of the final masses, there is a release of energy.

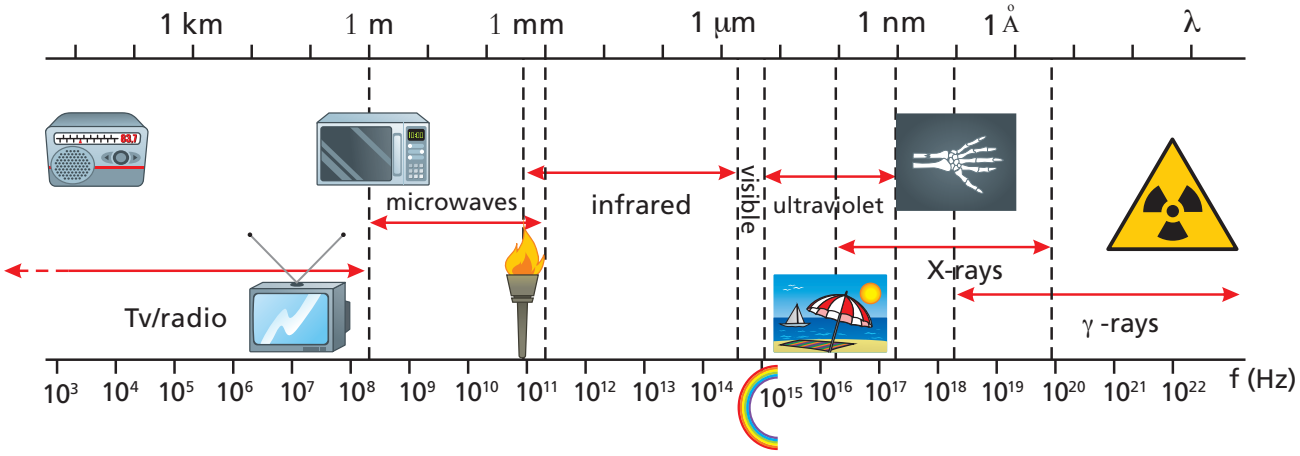
In order for fusion to occur, nuclei must overcome electrostatic repulsion as they approach each other; therefore it takes a great quantity of energy for the process to start; it then continues, since the energy released by the fusion is greater than that supplied and can be used to start other fusion reactions.

The fusion of hydrogen into helium is the main source of energy of the Sun and stars. The initial energy was probably supplied during the formation process, when particles came very close together, provoking a chain reaction.

The electromagnetic spectrum

The series of electromagnetic waves, classified according to their frequency or wavelength, is called electromagnetic spectrum. The names given to the various regions of the electromagnetic spectrum (FIGURE I-6) are related only to the way in which the waves are produced or observed, since they can all be described in terms of electric and magnetic fields and propagate through vacuum at the same speed, equal to the speed of light, **c**.

Figure I-6 –The electromagnetic spectrum



The magnitudes that characterize electromagnetic waves are their wavelength,[10] their frequency[11] (which varies inversely to the wavelength) or their energy (which is directly proportional to the frequency). Traditionally, one of these quantities is used to characterize the radiation of each region. The following are the characteristics of each region of the electromagnetic spectrum.

Radio waves

These are the electromagnetic waves with wavelengths between 1 m and several kilometers (frequencies under 10^8 Hz). They are used to broadcast information from radio and TV stations, since each of which will irradiate waves with a certain frequency. Radio waves can be generated by terrestrial sources, by the oscillation of electrons in the wires of electrical circuits. There are also external sources of radio waves, among which the Sun is the most important. **Radio astronomy** studies information coming from space through radio waves emitted by accelerated electrons from stars and other celestial systems.

TV waves

TV waves are short wavelength radio waves, between 1 m and 10 m (f between 10^8 Hz and 10^7 Hz) and, like radio waves, can be produced by electrical circuits. Frequency modulation (FM) radio wavelengths superimpose themselves on TV wavelengths.

Microwaves

These are electromagnetic waves with wavelengths between 1 mm and 1 m (f between 10^{12} Hz and 10^9 Hz) and can be produced by oscillators in electrical circuits. The energy of the microwave is used in physics laboratories in order to provoke transitions in the electrons of some atoms and thus obtain information about the material. The microwave oven was invented as the result of an event in a physics lab, when one of the researchers left a chocolate bar next to the equipment. He found that the chocolate had melted by absorbing the microwaves. This was due to the fact that the microwave energy was sufficient to heat the molecules through vibration.

Microwaves are also used for transmitting TV or telephone signals. Nowadays microwaves coming from outer space can be detected and provide information on the present and past history of the Universe.

Infrared radiation

This is the electromagnetic radiation with wavelengths greater than that of the visible light, between 0.7 μm and 1 mm, that is, frequencies just below those of red light (between 10^{14} Hz and 10^{11} Hz). In general, infrared radiation is obtained by vibrations or rotations of atoms or molecules. When an object absorbs infrared radiation, there is a change in its internal energy, which is why this radiation is called heat radiation. Celestial bodies emit infrared radiation that provides information complementary to that obtained by observing their emission of visible light.

---

[10] For very small values of wavelengths, the Angstrom unit is used: $1\text{Å} = 10^{-10}\text{m}$.

[11] Frequency is usually measured in Hertz: 1 Hz = 1 oscillation/s.

Visible light

This is the electromagnetic radiation to which the human eye is sensitive. Within the visible range, the frequency or wavelength variation will be perceived as a color variation, going from 4,000 Å (violet) to 7,000 Å (red) (frequencies between $7 \cdot 10^{14}$ Hz and $4 \cdot 10^{14}$ Hz).

Human eye sensitivity is not uniform for the entire visible range, being greater for yellowish green and lower for red and violet. In general, visible light is emitted when electrons make transitions in the outer layers of the atoms. The color of the light provides information regarding the atoms of the emitting object and therefore the study of the visible light emitted by the Sun and other stars provides information about their composition.

Ultraviolet radiation

Electromagnetic waves with wavelengths between 1 nm and 400 nm, that is, with frequencies immediately above that of the violet light (between 10^{15} Hz and 10^{17} Hz) are called ultraviolet radiation. They are produced by the transition of electrons in the outer or intermediate layers of atoms.

The Sun is a source of ultraviolet radiation, but most of it is absorbed by the ozone in the Earth's atmosphere.

The ultraviolet radiation absorbed by the human skin allows the production of vitamin D, which assists in the absorption of calcium from food. This radiation also causes tanning of the skin. Prolonged exposure to ultraviolet radiation, however, can cause skin burns and skin cancer.

Ultraviolet radiation can destroy bacteria; for this reason, it is used in the sterilization of surgical instruments and environments, air conditioning systems, etc., through the use of special lamps.

X-rays

These are the electromagnetic waves with wavelengths between 0.01 nm and 10 nm, (frequencies between 10^{16} Hz and 10^{19} Hz). X-rays are produced in transitions of electrons at the innermost levels of atoms or during deceleration of charged particles. The wavelengths of this radiation correspond to the spacing of the atoms in the solids, so it is possible to analyze the structure of the materials by X-ray scattering.

X-rays are also used in medical diagnoses, since they easily penetrate human tissue of low density, but are blocked by bone tissue.

In binary stars systems, where two stars orbit around their common center of mass, there is an emission of X-rays, thanks to the acceleration of the material that composes the stars. This radiation, however, cannot get through our atmosphere, and X-ray astronomy is carried out by orbiting observatories.

Gamma rays (γ-rays)

These are electromagnetic waves with wavelengths shorter than 10 pm (frequency greater than 10^{19} Hz). They can be emitted in transitions of the atomic nuclei or in nuclear reactions.

The γ-rays are highly penetrating and can cause cancer, damage to human tissue or genetic alterations. Their ability to destroy human tissues is used in medicine to eliminate cancerous tumors. They are also used for medical diagnoses, as we will see in Chapter III.

In γ-ray astronomy, the detection of this type of radiation provides information on nuclear processes occurring in the Universe.

High-frequency X-rays are similar to γ-rays, as they differ only in their origin. If we do not know what caused the radiation, we are unable to distinguish between X-rays and γ-rays.

There is also another type of radiation, generated by the annihilation of an electron and a positron. Although it does not come from the atomic nucleus, it is called γ radiation due to its high energy.

Ionizing radiation

High-frequency electromagnetic waves (X-rays and γ-rays) carry enough energy to cause ionization of atoms (stripping away electrons) whenever they strike a given material. They are called **ionizing radiation**. Waves with lower frequencies are not able to ionize materials, although they can produce other types of effects, depending on the energy they provide to the material. They are called **non-ionizing radiation**.

II - PRODUCTION AND DETECTION OF IONIZING RADIATION

As we saw in the previous chapter, there are natural sources of ionizing radiation. Most of the time, however, we need to use other radioactive material with specific characteristics in terms of energy, activity, half-life, etc. Several non-naturally occurring isotopes can be obtained through nuclear reactions.

Obtaining radioactive material

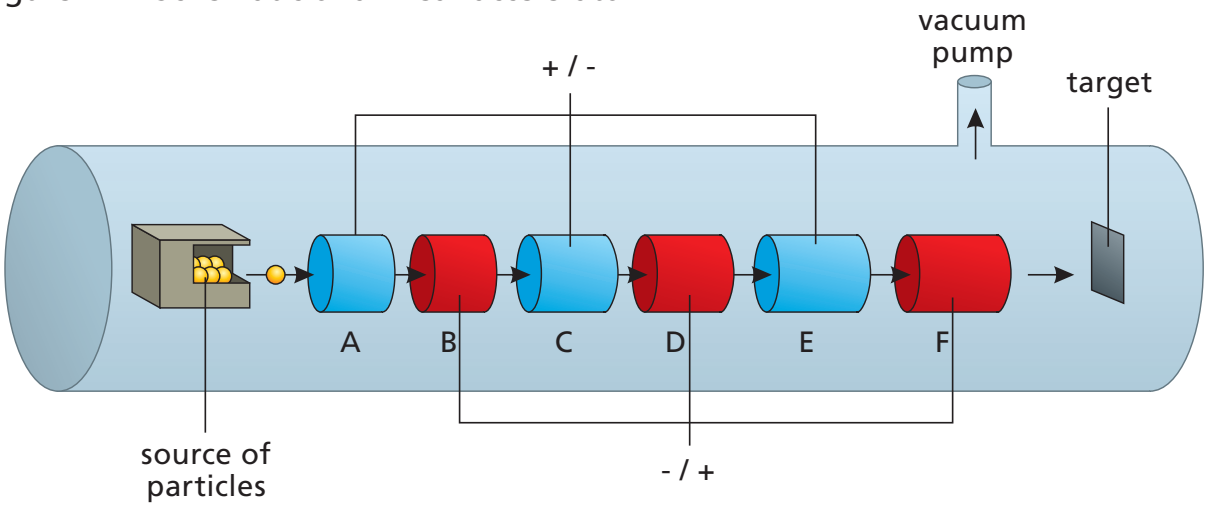
Several radioactive isotopes that are not found in nature can be artificially created by bombarding stable elements with neutrons, charged particles or photons of convenient energy. Beams of charged particles are obtained by using a **linear particle accelerator** or a **cyclotron**. In order to obtain a neutron beam, one needs either reactors or indirect reactions with charged particles, whereas **X-ray beams** can be produced with suitable intensity and energy levels.

Charged particles

In an electron accelerator, a metallic filament is heated in order to separate electrons from the metal atoms, after which the electrons are accelerated by an electric field and concentrated in a beam through the use of magnetic fields.[12] Some accelerators have several stages of acceleration, with alternating electric fields synchronized with the movement of the electrons, which accelerate them always towards the same direction (FIGURE II-1). The electron beam is then directed at a target and used for research or for manufacturing radioisotopes.

[12] When immersed in a magnetic field, charged moving particles are deviated from their path.

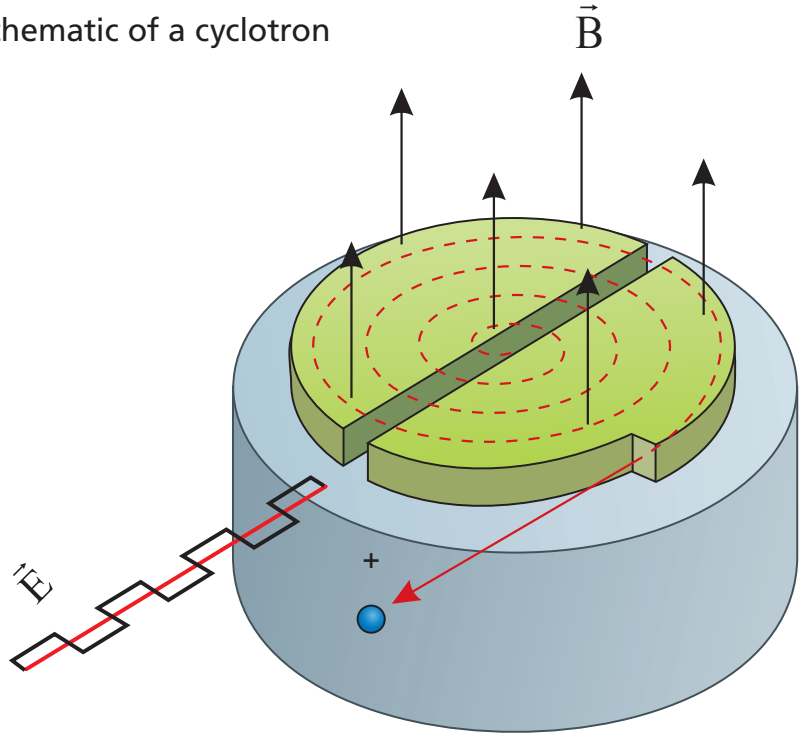
Figure II-1 - Schematic of a linear accelerator



Proton beams can be obtained in a similar way. In this case, the source of the protons is hydrogen gas, which is composed of molecules. The molecules are split into atoms, which are ionized by means of an electric discharge. A magnetic field separates the positive particles from the negative, after which the protons are accelerated by an electric field of suitable intensity.

In order to obtain high energy particles, it is necessary to have a very long linear accelerator. One can also use a more compact equipment called a cyclotron, where the particles, at the same time as they are accelerated, are deflected by magnetic fields, traversing a spiral path. At each loop, the electric and magnetic field values are adjusted, so that the particles progressively increase their energy; the accelerated particles are extracted through the rim of the device and move in a straight line until they reach the target (FIGURE II-2).

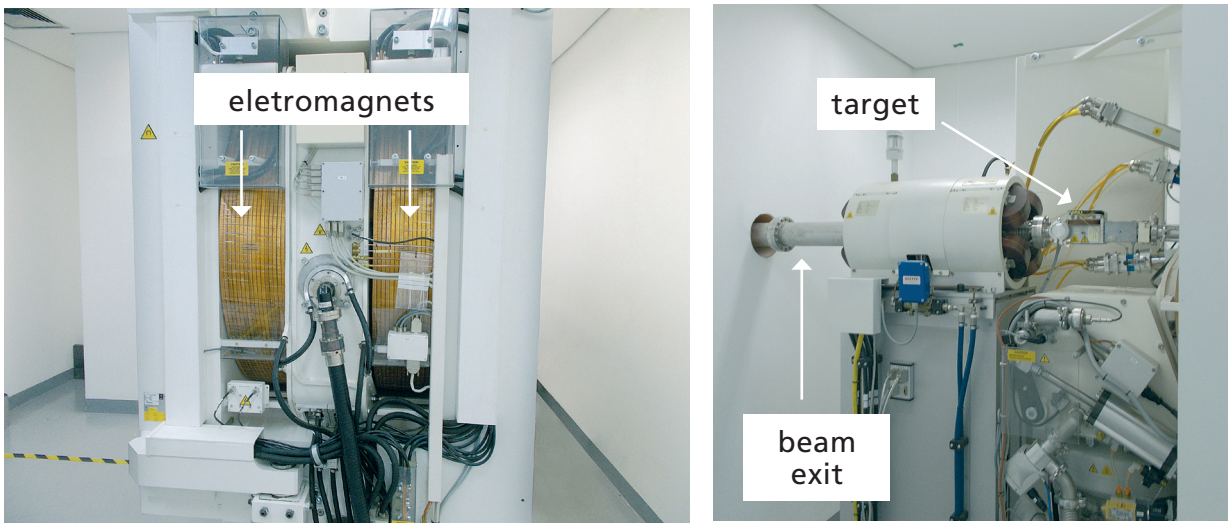
Figure II-2 – Schematic of a cyclotron



The charged particles move within two D-shaped structures. A uniform magnetic field $\vec{B}$ curves their trajectory; each time they cross the gap between the two structures, these particles are accelerated by an electric field $\vec{E}$.

Figure II-3 shows the cyclotron used in the CDTN – CNEN (*Centro de Desenvolvimento de Tecnologia Nuclear – Comissão Nacional de Energia Nuclear*, Brazil), where the electromagnets are placed in the vertical position, so that the magnetic field is horizontal. Protons resulting from the ionization of hydrogen gas are accelerated and collide with a target which may be solid, liquid or gaseous, consequently producing radioisotopes and/or an X-ray beam which may be used for other applications. The production of X-rays will be detailed later in this chapter.

Figure II-3 – Cyclotron (CDTN-CNEN, Brazil)



Neutrons

A neutron beam is easily obtained inside a fission reactor: the fission of uranium produces nuclei with a smaller mass and also neutrons, which will be available in large quantities inside the reactor, but with reduced energy, due to the existence of the moderator material contained in the reactor (usually water, or heavy water - where some hydrogen atoms have been replaced by deuterium, a hydrogen isotope containing one proton and one neutron). Another way to obtain neutrons is to use indirect reactions: charged particles from an accelerator strike a target where a reaction occurs in which neutrons are emitted with specific energy values.

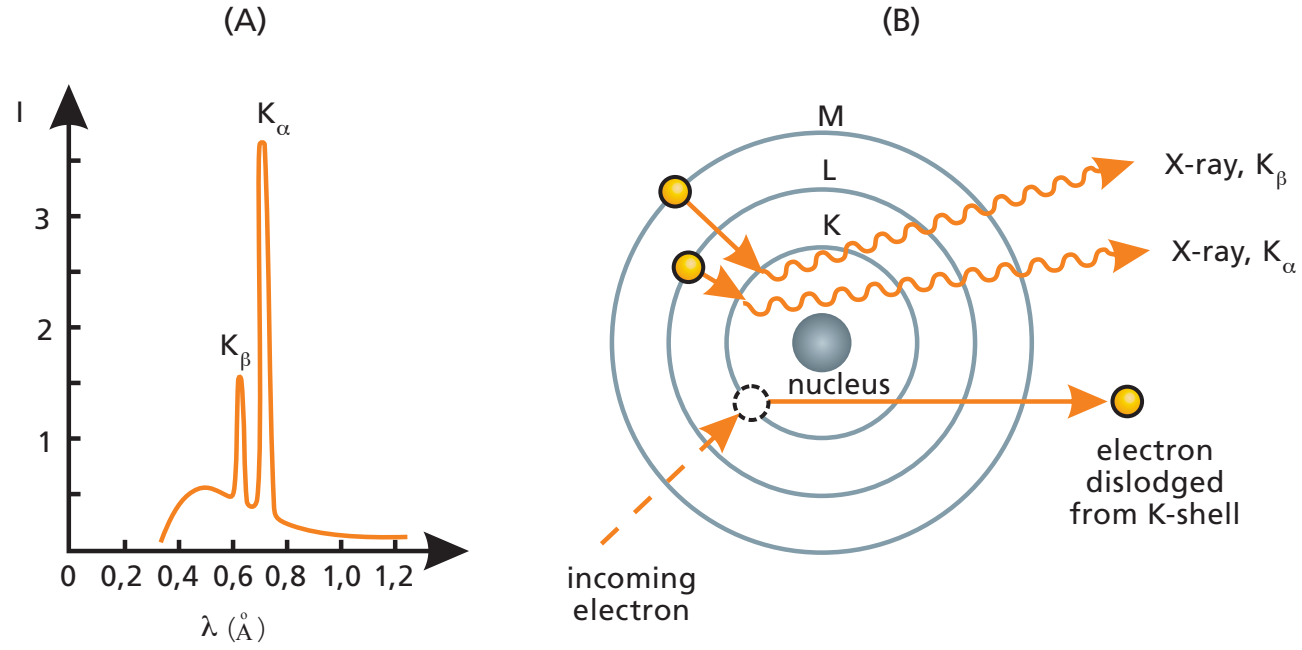
X-rays

The deceleration of charged particles leads to the emission of X-rays due to the phenomenon known as *bremsstrahlung*, German word for braking radiation. To achieve this, the beam from an accelerator is forced to hit a target (usually made of tungsten). The X-rays thus obtained have a continuous spectrum of energy, that is, their energy can have any value within a given range.

At the same time, upon hitting the target, the particles displace electrons from inside the atoms of that target (electrons which are at lower energy levels). These electrons are stripped, and higher-level electrons "fall" to take the place of the stripped electrons; the difference between the initial and final energy levels represents the order of magnitude of the energy of the X-rays. This results in the emission of X-rays with well-defined energy values for each target material, called characteristic X-rays.

Figure II-4 shows the energy spectrum of X-rays emitted by a molybdenum target.

Figure II-4 – X-ray emission by a molybdenum target



In (A), we see the energy spectrum of the X-rays emitted by a molybdenum target, where the peaks represent the characteristic X-rays of the material; in (B), we have the illustration of the emission of characteristic X-rays.

Obtention and characteristics of certain radioisotopes

Cobalt-60

Cobalt-60 is an emitter of energetic γ photons, and is produced by bombarding (stable) cobalt-59 with neutrons:

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

The neutron flux is obtained inside a nuclear reactor, where some of the absorber bars are replaced by cobalt-59 bars.

Cobalt-60 is unstable and decays into nickel-60:

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

In this reaction, γ photons are emitted with energies of 1.3 MeV and 1.1 MeV, in equal proportions. Cobalt-60 was used for some time in radiotherapy equipment, but gradually the sources were replaced by electron accelerators. Due to the high energy of γ emission, transportation and handling for the exchange of cobalt-60 sources require protection means such as shielding and remote control.

Technetium-99m[13]

Technetium-99m is a γ emitter, obtained from the decay of molybdenum-99; this is a product of uranium-235 fission in nuclear reactors:

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

Molybdenum-99 is chemically separated from other fission products and decays into metastable technetium:

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

The ${}^{99}_{42}\mathrm{Mo}$ has a half-life of 66 hours and can be transported from the producer to the hospital or clinic. The chemical extraction of technetium is made *in loco* from the Mo/Tc mixture; the metastable technetium ${}^{99\mathrm{m}}_{43}\mathrm{Tc}$ emits γ photons with 140 keV and decays with a half-life of 6 hours to the ground state of technetium-99:[14]

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

As the half-life of Mo-99 is 10 times greater than that of Tc-99m, it can be stored, allowing chemical extraction to be carried out when needed. Therefore, even with a half-life of only 6 hours, Tc-99m can be used within approximately one week after arrival at its destination.

After the decay of technetium-99m into technetium-99, the latter decays into ruthenium-99 with a β^{-} emission; the half-life of this emission is quite long, and therefore the activity (emissions per unit of time) is very low, when compared to that of the metastable isotope:

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

Fluorine-18

Fluorine-18 is emitter of positrons and can be obtained by bombarding oxygen-18 with protons.

Oxygen-18 is a stable isotope of oxygen and exists in small proportion in nature. It is possible to carry out an enrichment of water, by concentrating the molecules in which the oxygen appears in this isotopic form.

For the production of fluorine-18, accelerated protons are used in a cyclotron, where hydrogen gas (H_2) is ionized, producing protons and electrons. The protons are accelerated and sent to collide with an enriched water target. When these protons reach nuclei of oxygen-18, the following reaction occurs:

$$ {}^{18}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{p} \rightarrow {}^{18}_{9}\mathrm{F} + {}^{1}_{0}\mathrm{n} $$

---

[13] The symbol m indicates that the isotope is in a metastable form.

[14] This is the main decay path; in about 10% of cases, the phenomenon called internal conversion may occur: an electron absorbs the energy of the γ-ray and is ejected, ionizing matter in its vicinity and increasing the exposure.

Fluorine-18 is unstable, and the main decay reaction involves the emission of a positron:

$$^{18}_{9}F \rightarrow ^{18}_{8}O + \beta^{+} + \nu_{p} \qquad T_{1/2} = 110 \text{ min}$$

Soon after the emission, the positron (β^{+}) finds an electron (e-) in its vicinity[15]; they annihilate each other, with the emission of 2 photons of 0.511 MeV in opposite directions:

$$\beta^{+} + e^{-} \rightarrow 2\gamma$$

The decay product, oxygen-18, is stable and non-toxic.

Iodine-131

Iodine is obtained from the decay of tellurium-131. Tellurium-131 is produced in a reactor, by bombarding tellurium-130 with neutrons in order to form tellurium-131, which in turn decays into iodine-131 by emission β^{-}:

$$^{130}_{52}Te + ^{1}_{0}n \rightarrow ^{131}_{52}Te + \gamma$$

$$^{131}_{52}Te \rightarrow ^{131}_{53}I + \beta^{-} + \overline{\nu_{e}} \qquad T_{1/2} = 25 \text{ min}$$

After the bombardment, the chemical separation of iodine is carried out, for example, by the evaporation of the gas through heating.

Iodine-131 decays into xenon-131 (excited state) by emission β^{-}, with energy of 606 keV; then the xenon decays into its ground state by emission of a γ photon with energy of 364.5 keV[16] and half-life of 12 days.

$$^{131}_{53}I \rightarrow ^{131}_{54}Xe^{*} + \beta^{-} + \overline{\nu_{e}} \qquad T_{1/2} = 8 \text{ days}$$

$$^{131}_{54}Xe^{*} \rightarrow ^{131}_{54}Xe + \gamma \qquad T_{1/2} = 12 \text{ days}$$

Iridium-192

Iridium is one of the most dense metals; its density is approximately 23 g/cm^3. Iridium-192 can be obtained in a reactor, through the capture of neutrons by iridium-191:

$$^{191}_{77}Ir(n,\gamma)^{192}_{77}Ir$$

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[15] Usually, the distance traveled by the positron until it meets an electron and they annihilate each other is between 6 mm and 10 mm.

[16] This emission occurs in about 80% of cases; γ emission may also occur with lower energy, if the nucleus does not decay directly to its ground state.

The radiation energy varies between 0.2 and 0.6 MeV and the radioisotope decays mainly into platinum-192, which is stable:[17]

$$^{192}_{77}\mathrm{Ir} \rightarrow {}^{192}_{78}\mathrm{Pt} + {}^{0}_{-1}\beta + \gamma \qquad T_{1/2} = 74 \text{ days}$$

Carbon-11

Carbon-11 is produced in a cyclotron by bombarding protons over a gaseous nitrogen target (N_2), which contains 2% of oxygen (O_2):

$$^{14}_{7}\mathrm{N}(\mathrm{p},\alpha)^{11}_{6}\mathrm{C}$$

Carbon-11 combines with oxygen, forming mainly $^{11}CO_2$; ^{11}CO is also formed and must be separated before the next stages of production take place. Carbon-11 decays with positron emission:

$$^{11}_{6}\mathrm{C} \rightarrow {}^{11}_{5}\mathrm{B} + {}^{0}_{1}\beta^{+} \qquad T_{1/2} = 20 \text{ min}$$

The $^{11}CO_2$ can be used to replace a few carbon-12 atoms with carbon-11 in organic molecules, through chemical procedures, thus obtaining different radiopharmaceuticals (substances prepared using radioisotopes, for diagnostic or therapeutic use).

Cesium-137

Cesium-137 is obtained as a fission product of uranium-235 in nuclear reactors:

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

Cesium is chemically separated from other fission products and prepared as cesium chloride (CsCl) for use as a source of β and γ radiation.

Cesium-137 decays with a half-life of 30 years into unstable barium-137, which, in turn, decays to its ground state with a half-life of 153 s, emitting γ rays:

$$^{137}_{55}\mathrm{Cs} \rightarrow {}^{137}_{56}\mathrm{Ba}^{*} + {}^{-1}_{0}\beta^{-} + \nu_{\mathrm{p}} \qquad T_{1/2} = 30 \text{ years}$$

$$^{137}_{56}\mathrm{Ba}^{*} \rightarrow {}^{137}_{56}\mathrm{Ba} + \gamma \qquad T_{1/2} = 153 \text{ s}$$

[17] In about 5% of the cases, iridium-192 decays into osmium-192 (a stable isotope), by electron capture: $^{192}_{77}\mathrm{Ir} + {}^{0}_{-1}\beta \rightarrow {}^{192}_{76}\mathrm{Os} + \gamma$; in this reaction, the γ radiation energy and the half-life are of the same order of magnitude as those of the decay into platinum; other radionuclides which have a short half-life (between 30 min and 19 h) may also be formed in small amounts.

The energy of the γ emission is 662 keV, and the half-life of the decay chain is 30 years. These physical characteristics allow them to be used in hospital and industrial equipment. However, the separation of cesium from other elements is complicated, and for economic reasons, for use in brachytherapy, it has been replaced by ^{192}Ir, which has 8% of its emission with energy of 604 keV, therefore close to the one of the ^{137}Cs. In addition, cesium chloride is obtained in the form of a powder which, in the event of an accident, such as the loss of encapsulation, can spread easily and cause contamination.

Interaction of radiation with matter

When ionizing radiation strikes matter, there may be chemical or nuclear transformations, emission of new particles or the start of a series of nuclear reactions.

Electromagnetic radiation

Electromagnetic radiation (X-rays and γ rays) interacts with matter in three different forms: the photoelectric effect, the Compton effect, and the production of pairs.

In the **photoelectric effect**, a photon removes an electron bound to an atom as it strikes against it. It is necessary that the photon has energy equal to or greater than the binding energy between the electron and the atom, then the emission of electrons only occurs from a given threshold of energy. If the photon has more energy than this threshold, the energy balance is recovered as the kinetic energy of the ejected electron.[18] This phenomenon occurs for lower energies of the photon (FIGURE II-5A).

In the **Compton effect**, a photon and a free or weakly bound electron behave like two colliding particles; as a result, we have a change in the trajectories and energies of both, following the laws of energy and momentum conservation. This phenomenon occurs for intermediate energies of the photon (FIGURE II-5B).

If the photon energy is quite high, **pair production** may occur: the photon disappears, giving rise to an electron and a positron. The minimum energy of the photon must correspond to the masses of the electron and the positron. If the energy of the photon is greater than the minimum value, the energy balance will be converted into kinetic energy of the particles created. The pair production must occur in the vicinity of a nucleus, which recoils, in order to conserve moment (FIGURE II-5C).

The positron thus created soon finds an electron, and the pair annihilates itself, generating photons of energy corresponding to the masses and energies of the pair.[19]

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[18] After the emission of the photoelectron, the atom accommodates emitting X-rays or a loosely bound electron, which is called an Auger electron.

[19] The radiation emitted in a pair annihilation is called γ radiation, although it does not have nuclear origin.

Figure II-5 – Illustration of the photoelectric effect (A) of the Compton effect (B) and pair production (C)

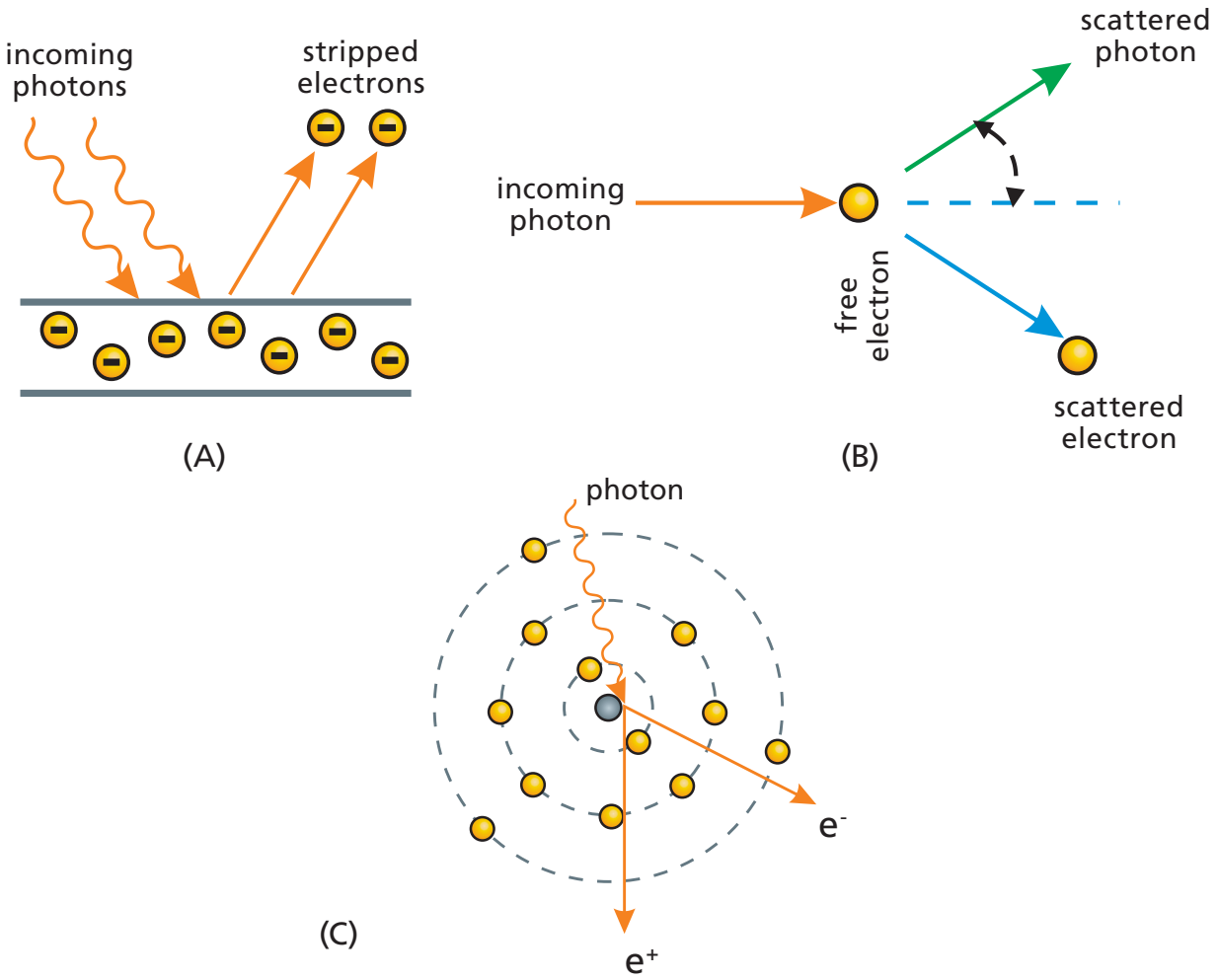
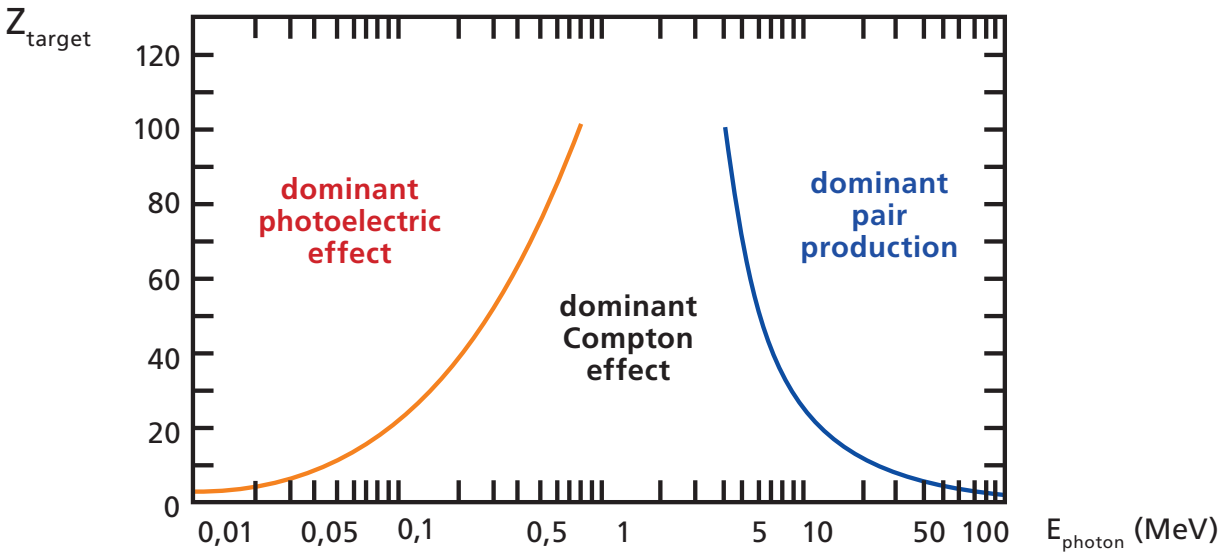


Figure II-6 shows the energy range where each of the three phenomena is most likely to occur, as a function of the size of the target nucleus.

Figure II-6 - Interaction of a photon with matter, as a function of its energy and the atomic number of the target element



Charged particles

Charged particles are more likely to collide with atoms than to interact directly with nuclei. They then interact with matter primarily by excitation or ionization of the atoms. When they collide with the nuclei, the particles are absorbed and affect the nuclear structure. During interaction with matter, the charged particles undergo deceleration or change in trajectory and emit electromagnetic radiation, while losing energy.

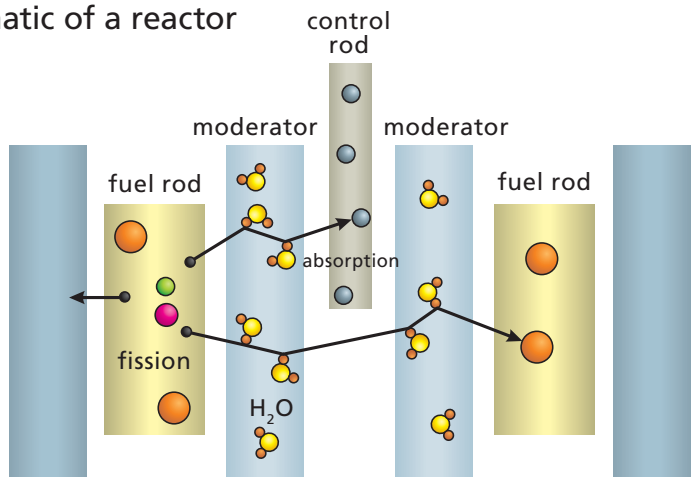
The electrons interact with the matter causing ionization or emitting braking radiation (*bremsstrahlung*). α particles cause ionization or capture electrons, becoming neutral He atoms. The travel range of the α particles is always very small, and the energy transfer occurs at the end of its trajectory. Fission fragments have large masses: they can cause ionization, but their range is still smaller.

Neutrons

Since they have no electric charge, neutrons interact with matter by scattering or capture. In scattering, neutrons collide with other particles and there is energy exchange. The exchange is most effective if the colliding particles have the same or similar masses. The capture of neutrons takes a nucleus to an excited state, provoking nuclear reactions or the fission of the nucleus.

These two types of neutron interaction occur in a fission reactor. Taking as an example a uranium-235 reactor: we know that the ^{235}U captures slow neutrons and suffers fission, emitting fast neutrons. In order for the reaction to continue, it is necessary to decrease the kinetic energy of the neutrons emitted;[20] this is achieved by forcing them to collide with atoms of mass slightly larger than their own. Usually, the following are used: light water (scattering by hydrogen nuclei), heavy water (more effective moderation by deuterium atoms),[21] or bars of graphite or of metallic sodium. Graphite and sodium nuclei are slightly larger than the neutron and will take up most of the energy after the collision. The simplified schematic of a reactor is shown in Figure II-7.

Figure II-7 – Schematic of a reactor



Neutrons that reach the fissile material of the fuel rod cause fission, with release of other neutrons; these are thermalized (have their kinetic energy reduced) when they collide with the nuclei in the moderator; while some neutrons are captured by the nuclei of the control rods, only a few of the released neutrons will be available to start new fission processes.

[20] Slow neutrons are called thermal neutrons, as their energy is the one they would have at ambient temperature. The action of reducing the neutron energy is called thermalization of the neutron.

[21] We call "light water" the water in which the nuclei of the two hydrogen atoms have only one proton, and no neutrons; in "heavy water", at least one of the hydrogen atoms has one or more neutrons at its core.

Interaction of radiation with living beings

In living beings, when ionizing radiation strikes organs or tissues, it first provokes physical effects; then chemical effects and, lastly, biological effects. Upon impacting a cell, radiation can directly ionize a target molecule or ionize the water contained in the cell, generating free radicals, which, in turn, react with the target molecule. The second hypothesis is more likely to occur because water is the main component of the cell. Radiation can damage any component of the cell, but the most severe damage is caused when the DNA inside the cell's nucleus is reached.

After the ionization, and depending on the degree of damage to the cell nucleus, the following may occur:

a) repair of the damage so the cell continues to reproduce normally;
b) reproduction of the cell, but death of offspring;
c) mutations in the DNA of the cell and transmission of these mutations to the offspring;
d) or, if the damage is very severe, the cell may die ("apoptosis"). This is desirable, in order to prevent the damage from being transmitted.

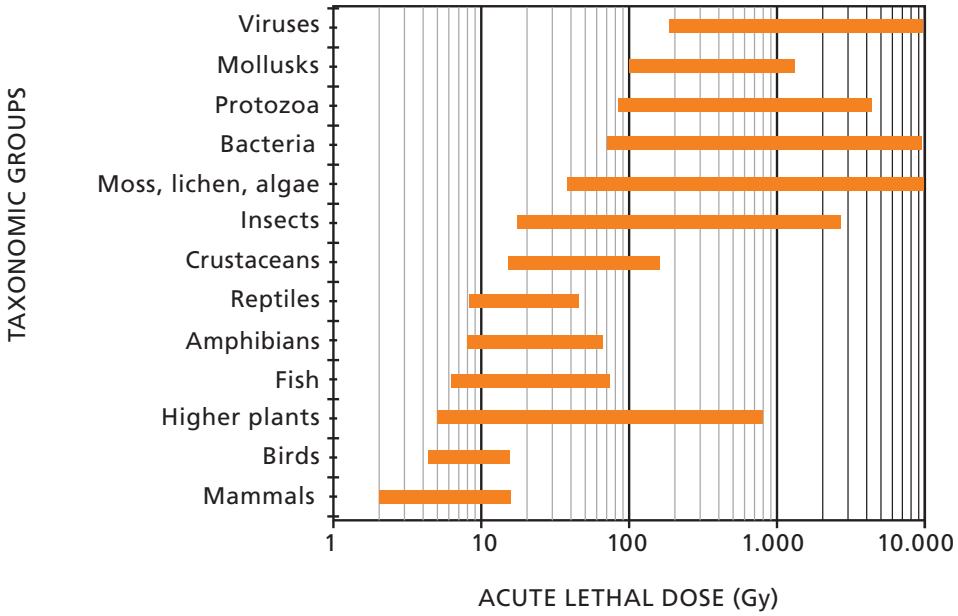
Regarding the cell cycle, the most radiation sensitive cells are those in the mitosis stage (cell division) and those that are not differentiated. This is because during mitosis the DNA is replicated, and any damage can prevent cell reproduction; the undifferentiated cells divide more often than the differentiated ones and need all the information contained in the DNA, whereas the differentiated cells use only part of the DNA information and replicate less frequently (or in some cases, they do not even replicate at all). Then, if the damage affected only part of the DNA, it may not be important to the differentiated cells. Following this reasoning, we can conclude that, in the human body, the cells most affected by the ionizing radiation are those of bone marrow and some components of the blood (for example, the leukocytes), which replicate very fast; followed by the cells in the gastrointestinal tract walls and in the reproductive organs, which also reproduce considerably fast. The least affected cells are neurons and muscle cells, which do not multiply.

Lethal dose for fauna and flora components

Living organisms have distinct resistances to the biological effects of ionizing radiation. In general, the greater its organic, structural and neurological complexity, the lesser its resistance. The more simplified the organism, the greater its resistance[22]. Figure II-8 shows approximate lethal dose ranges for different living organisms.

[22] This rule is known as the Law of Bergonié-Tribondeau, in tribute to the two French doctors who first established it in 1906: J.A.Bergonié (1857-1925) and L.M.Tribondeau (1872-1918).

Figure II-8 – Lethal dose of radiation for various living organisms



The dose is given in Gray units (Gy), representing the amount of energy absorbed per unit mass. (Based on: UNSCEAR 2008, Report to the General Assembly, Annex E. Available at: <http://www.unscear.org/docs/publications/2008/UNSCEAR_2008_Annex-E.pdf> Acessed Sept 2017).

Radiation detection

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 energy of the radiation is transformed into an electric quantity, which can be easily and accurately measured.

First detectors

The first radiation detector was accidentally used by Becquerel: he wrapped a radioactive mineral with photographic film and later found that the film had been darkened by radiation, which at the time was of unknown origin. The photographic emulsion consists of grains of silver halide, mostly bromide (AgBr). The radiation ionizes the Ag ions turning them into metallic silver. After being developed with revealing and fixing solutions, the film shows the regions affected by the radiation. Photographic emulsions were used early in the past to control the radiation received by professionals working with ionizing radiation. They were replaced by thermo-luminescent dosimeters, which will be described later.

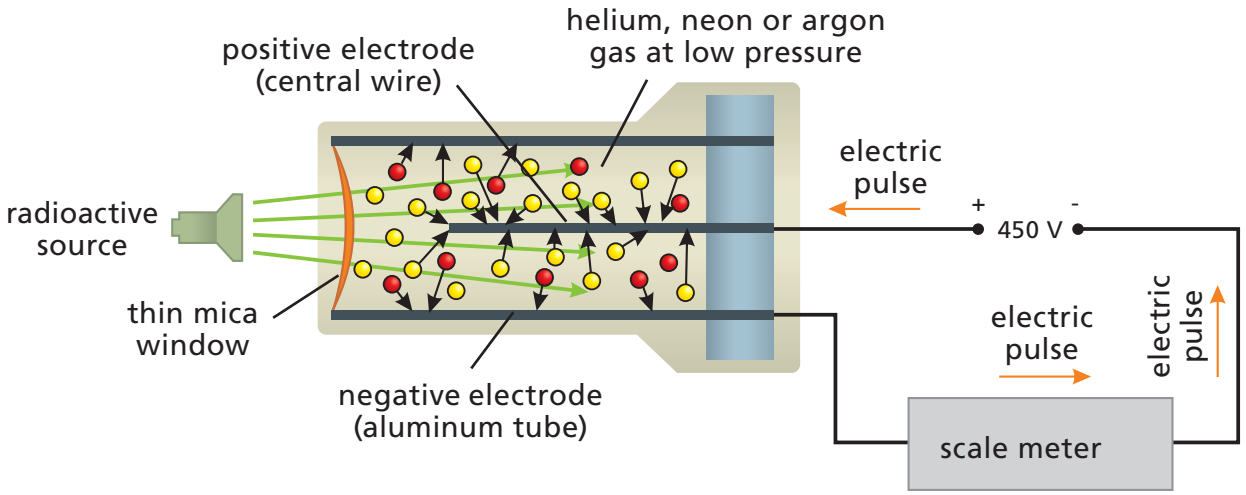
Current detectors

The most common detectors currently used are gas detectors, scintillators and semiconductors.

In gas detectors, the radiation ionizes the gas placed in a chamber, causing the conduction of electric current through a circuit. The best known of these is the **Geiger-Müller counter**, named after the physicists who invented it in the early 20th century. It consists of a cylindrical metal chamber that has a central conductive wire in it and is filled with gas at low pressure. The wire and the metal casing are subjected to an electrical potential. The

radiation that penetrates the chamber ionizes the gas, the ions move through the potential causing an electrical discharge when they reach the filament or the case (FIGURE II-9). These detectors are compact and are portable for external measurements.

Figure II-9 – Schematic of a Geiger-Muller counter



Scintillators

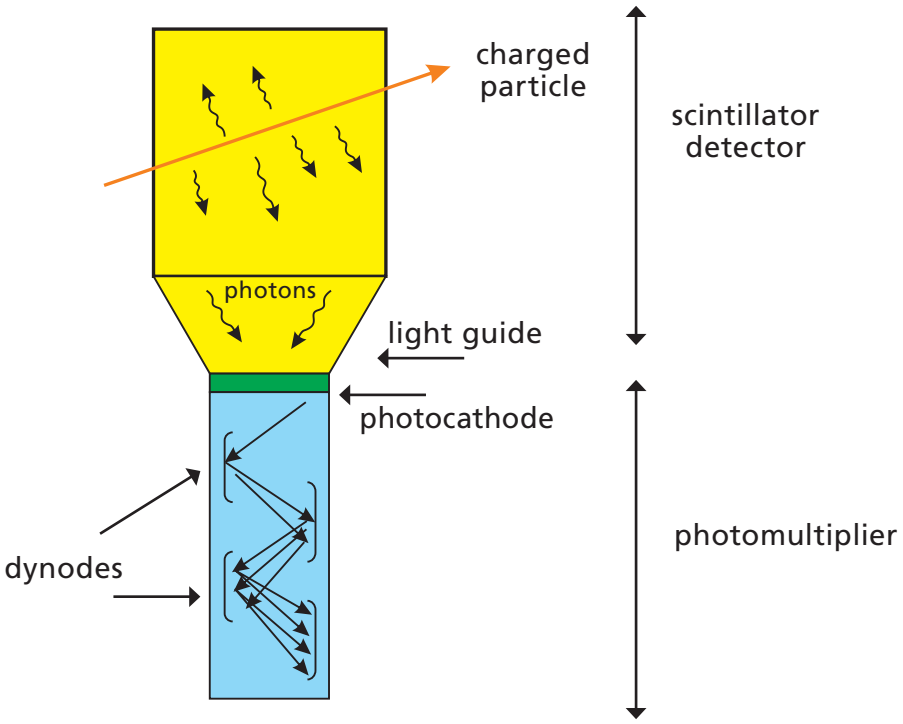
Currently, most of the detectors use **scintillators**, which are crystals that emit light after the ionization caused by the passage of radiation, or **semiconductor detectors**: in these, the radiation hits a p-n junction,[23] creating pairs of electrons and holes which later meet and emit an electric or luminous signal, multiplied and analyzed by electronic devices. The various types of detectors are adapted in order to characterize the kind of radiation, the amount of particles or their energy. In general, ionization processes are efficient for photons and charged particles. In order to distinguish different forms of radiation, there are shields that eliminate the less penetrating particles from the detection, allowing us to compare the measurements made with the shield and without it.

The most common type of scintillator is the sodium iodide detector with small amounts of thallium [NaI(Tl)], but there are also scintillators that use organic or plastic crystals; the photons emitted by the scintillation generate electrons, through the photoelectric effect; the electrical signal needs to be amplified and analyzed using electronic devices, for example, by a **photomultiplier tube**. Figure II-10 shows a scintillator detector coupled to a photomultiplier.

Radiation excites the atoms in the scintillating crystal, and when they return to the ground state, they emit photons. The emitted light is directed to the photomultiplier and it strikes a metal plate, from where it strips electrons due to the photoelectric effect. The stripped electrons are accelerated by an electrical potential between the photoelectric plate and another plate, called dynode; when colliding with the dynode, the electrons strip other electrons, which are accelerated towards a second dynode, and so on. At each collision, the number of electrons is multiplied; at the end of the process, there are enough electrons to be measured as an electric pulse.

[23] A junction p-n is a region where a material containing excess free electrons (n-type, negative) is superimposed upon a material lacking free electrons (p-type, positive). The excess or lack of electrons is obtained by inserting in the semiconductor small amounts of other atoms, called dopants or impurities..

Figure II-10 – Schematic of a scintillator detector, with photomultiplier



An example of a scintillation detector is the scintillation camera used in Nuclear Medicine for diagnostic exams with radioisotopes that emit γ radiation. In this chamber, the scintillator crystal, when bombarded with γ radiation, emits photons in the visible range. The photons strike a series of small photomultipliers that have their signals compared to each other. It is possible to locate the source of the scintillation by checking which photomultipliers showed the strongest signal. After analysis, the electrical signals are sent to a computer that builds an image of the object that emitted the radiation.

By taking measurements of the emission at various angles around the emitter, a three-dimensional reconstruction of the image (tomography) can be obtained.

The use of the scintillation camera is described in Appendix A2.

Scintillators with coincidence circuit

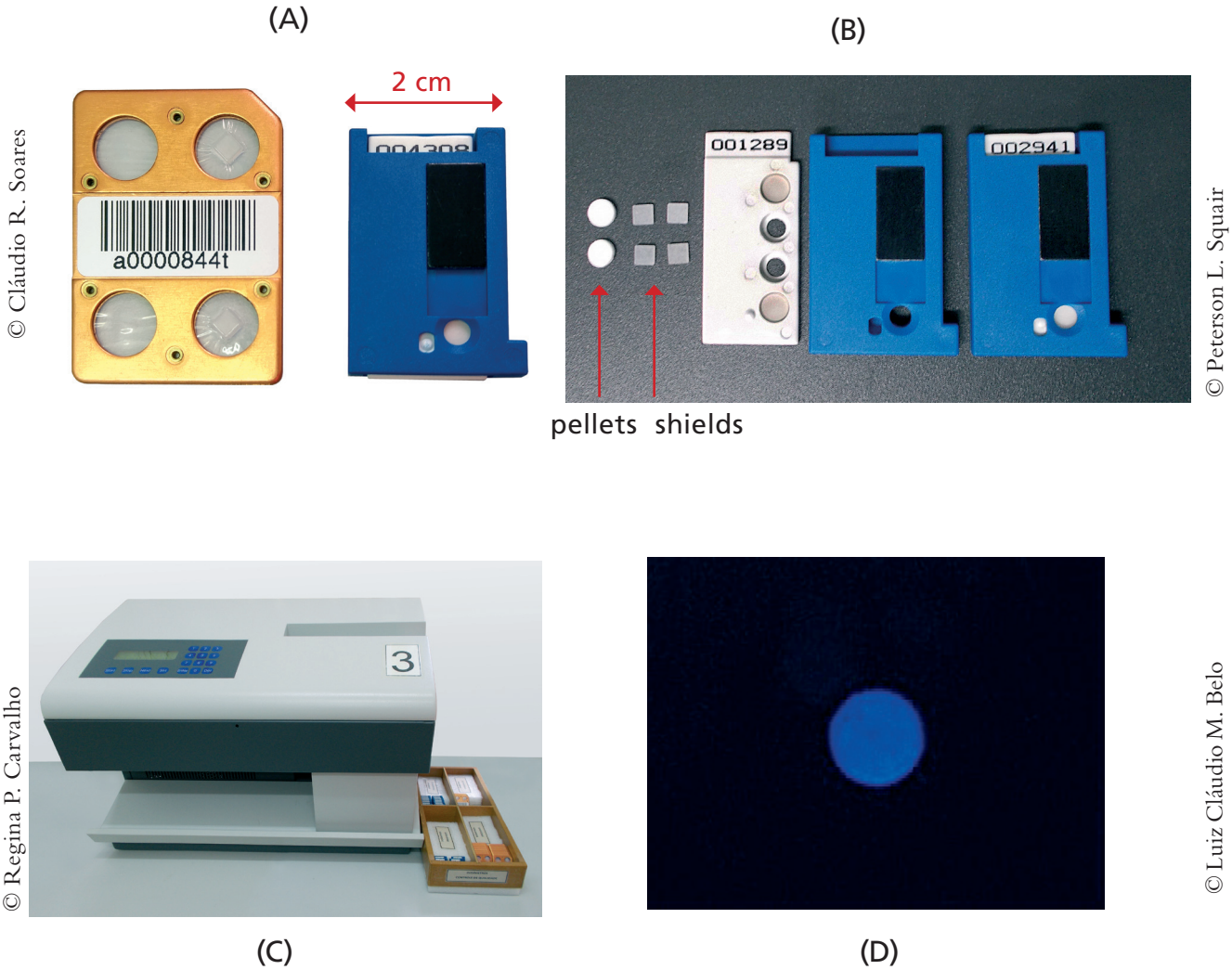
In order to detect the γ emission from pair annihilation, it is necessary to use a more sophisticated scintillation system. Annihilation occurs when a positron encounters an electron and the two annihilate each other, generating two γ photons whose sum of energy is equivalent to the masses of the two particles. The two photons are emitted in opposite directions. In this case, detection is accomplished through two sets of small scintillators, placed on opposite sides of the emitter. The signals will only be taken into account when they are detected simultaneously by two photomultipliers, placed at 180° from each other, that is, when there is a temporal coincidence between the two signals. The photomultiplier position indicates the point where annihilation occurred. This device is used for the detection of β^+ emitters, since annihilation occurs in a region that is very close to that of emission.

Semiconductor detector

The principle of operation of semiconductor detectors is based on the fact that, in semiconductor materials, the electrons completely fill the energy level we call the **valence band**, from where it is very difficult to displace the electrons. The higher energy level, called the **conduction band**, is empty and could allow the flow of electrons, but there is a separation between the two bands (the **forbidden band**), which must be overcome by supplying energy to the material.

An example of a semiconductor detector is the **TLD** (*Thermoluminescent Dosimeter*). It is a small detector placed inside a plastic holder, carried by a person exposed to radiation, and analyzed every 30 days to check the radiation dose received by the worker (FIGURE II-11).[24]

Figure II-11 – Thermoluminescent Detectors (TLDs)

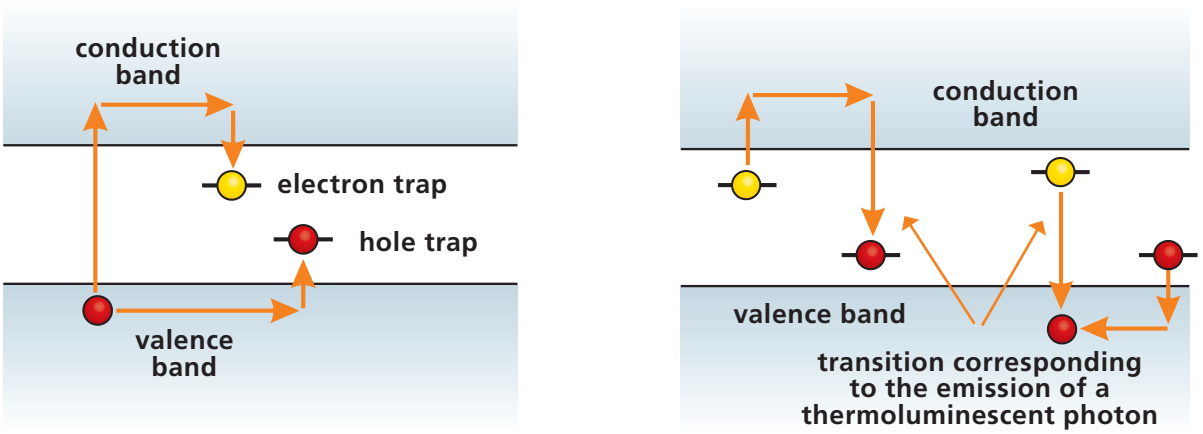


(A): detector for calibration (golden) and for use in badges (blue); (B): disassembled detector, showing the semiconductor pellets and shields; (C): equipment for measuring the dose absorbed by the TLD; (D): luminescence of a heated pellet

[24] TLDs may also be attached to rings, wristbands or safety glasses, used to measure absorbed doses in the hands or eye lenses, when these may receive larger exposures than the rest of the body.

The TLD is constructed of a pellet of semiconductor material - generally CaF or LiF, containing impurities; the impurities create levels of energy in the forbidden band, which act as "traps" for electrons or "holes".[25] Upon receiving the radiation, the crystal is ionized, and the emitted electrons become trapped in the impurities (FIGURE II-12). Later, in order to determine the dose of radiation absorbed by the TLD, it is heated and the trapped electrons return to their initial energy levels and emit photons. A photomultiplier transforms the photons into electrical pulses. The intensity and number of electrical pulses inform the radiation dose received and its energy. After heating, the TLD returns to its original state and can be used again.

Figure II-12 – Energy levels of a semiconductor material containing impurity



The electrons of the semiconductor are in the valence band; in order to reach the conduction band, they need to absorb a large quantity of energy. The presence of an impurity creates intermediate levels between the conduction and valence bands, which trap the electrons. Through heating, the trapped electrons return to their fundamental level and emit photons.

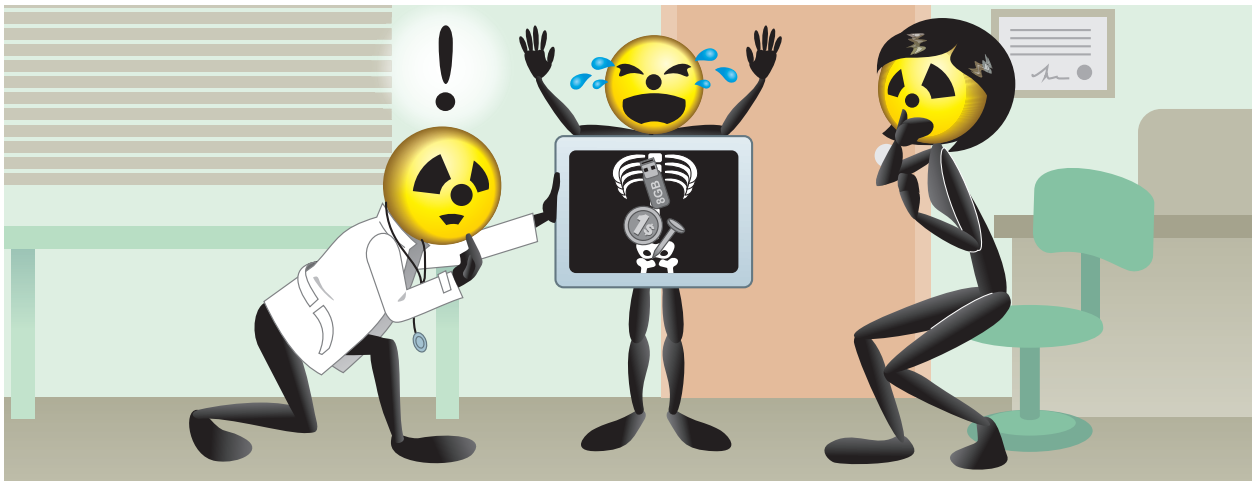
In order to detect different types of emission, several pellets are used on the same support, placing convenient shields in some of them. The comparison between the radiation received by the covered and uncovered pellets will inform the type of radiation received by them.

Another type of detector is the **germanium detector**, used in radioisotope production labs. The germanium element is a semiconductor with a narrow band. The incidence of γ radiation promotes the transfer of electrons from the valence band to the conduction band. When an electric field is applied to the crystal, the electrons move, generating electric pulses which can be measured; the number of pulses is proportional to the number of γ photons received by the detector.

The germanium detector functions at the liquid nitrogen temperature (-196 °C). This is necessary due to the narrowness of the forbidden band. At higher temperatures, the thermal energy of the electrons is enough to overcome the energy barrier of the forbidden band. If there is no cooling of the detector, the measurement of the pulses produced by the electrons will take into account not only those produced by the absorption of γ photons, but also those produced by the thermal agitation of the crystal.

[25] The "holes" are lacks of electrons and behave as if they were "positively charged electrons".

III - USES OF IONIZING RADIATION IN PROMOTING HEALTH



When ionizing radiation travels through a material, it may cause **changes** in the atoms and molecules, while, at the same time, the radiation itself is **attenuated**. The consequences of these changes are used for diagnosis of illnesses, treatments, sterilization of hospital supplies or food, control of disease transmitting insects, among other applications in the field of health care. Radioisotopes are chosen with regard to their energy and characteristic half-life bearing in mind the intended specific use.[26]

Diagnosis

X-rays

The attenuation of X-rays when traversing matter depends on the atomic number and density of the material. For example, in our body, bones attenuate radiation more than soft tissue; attenuation may also indicate tissue changes (inflammation, infection or the presence of unexpected formations, such as benign or malignant nodules). It is then possible to use the radiation to acquire an anatomical image from the capture of the modified X-rays transmitted.

X-rays are collimated toward the patient's organs by adjusting the equipment for reaching the region of interest. In order to avoid scattered radiation to regions of the body that do not need to be irradiated, protections for specific organs such as gonads or thyroid are used. In diagnostic radiology, X-rays are attenuated differently, depending on the density of the organ under study. The simplest equipment uses photographic plates for obtaining the image. In more sophisticated equipment, the photographic plate is replaced by scintillator detectors, whose information is processed with digital techniques, producing images directly on the screen of a computer.

[26] This chapter shows only some of the many applications of radiation in medicine. These examples were chosen in order to display the most important characteristics of the radioisotopes in each case.

γ–*rays*

The γ-rays allow the acquisition of a physiological image of internal organs using radiopharmaceuticals, obtained by incorporating γ emitting radioisotopes into certain molecules. These radiopharmaceuticals are administered to the patient by intravenous, intramuscular or oral means, and are absorbed preferentially by given organs.

A gamma scintillation detector can rotate around the patient or do a horizontal sweep, recording the locations of radiopharmaceutical accumulation. Subsequently, using computational tools, a 3-dimensional image is constructed, allowing the construction of a dynamic image of the organ of interest. The processes of image acquisition and processing are explained in Appendix 2.

γ radiation has the advantage of monochromaticity (the photons emitted in a certain transition have the same energy). This is important to differentiate the photons emitted by the radiopharmaceutical from other photons, which may accidentally be detected.

Radiopharmaceuticals for diagnosis

Radiopharmaceuticals are substances prepared with the use of radioisotopes, which will be absorbed preferentially in the organs to be analyzed or treated. The radioisotope is chosen according to its properties (half-life, type and energy of emission, as well as ease of transportation). The radiopharmaceutical is prepared and shipped to the place of application, following radiation safety regulations to protect the persons involved in its handling.

The radioisotope most used in diagnostics is $^{99m}_{43}Tc$ (technetium-99 meta-stable). One advantage of technetium-99m is that it has valences of 4 to 7, so different molecules can be marked; which makes it possible to obtain several different radiopharmaceuticals, used for diverse types of diagnoses, according to the organ being studied. Another advantage is that it is a γ emitter and not a β emitter, since the scintillation chambers used for diagnosis only detect γ radiation, thus avoiding unnecessary radiation to the patient. In addition, the energy of its γ emission (140 keV) is sufficient for it to escape from the patient's body and be easily detected.[27]

The $^{99m}_{43}Tc$ is administered to the patient as a salt (pertechnetate), or bound to a molecule that will be preferentially absorbed in an organ of the body.

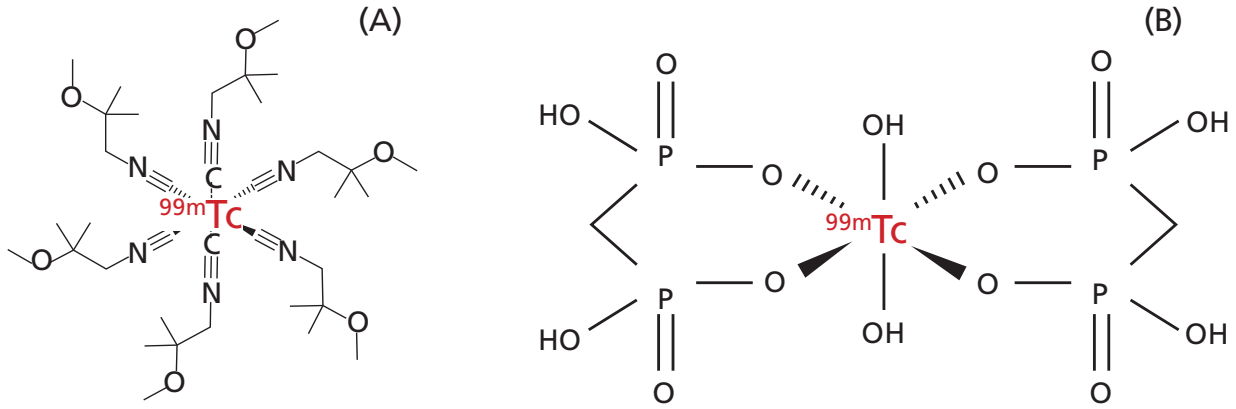
Pertechnetate accumulates mainly in regions that are undergoing bone tissue regeneration (fractures, inflammation or tumors).

The technetium attached to exametazime accumulates in the brain, allowing for the study of blood flow alterations within this organ. Another widely used radiopharmaceutical is "Sestamibi": in which one $^{99m}_{43}Tc$ atom is bound to 6 molecules of MIBI (methoxyisobutylnitrile); this compound is absorbed preferentially by the heart muscles and is used in cardiological diagnoses. The $^{99m}_{43}Tc$, when linked to MDP (methyl diphosphonate), is preferentially absorbed in bones and allows the investigation of bone metastases (FIGURE III-1).

---

[27] The efficiency range of the most commonly used NaI detectors in this case is from 100 keV to 300 keV, which comprises the emission energy spectrum of Tc-99m.

Figure III-1 – ^{99m}Tc-sestamibi (A) and ^{99m}Tc-MDP (B)



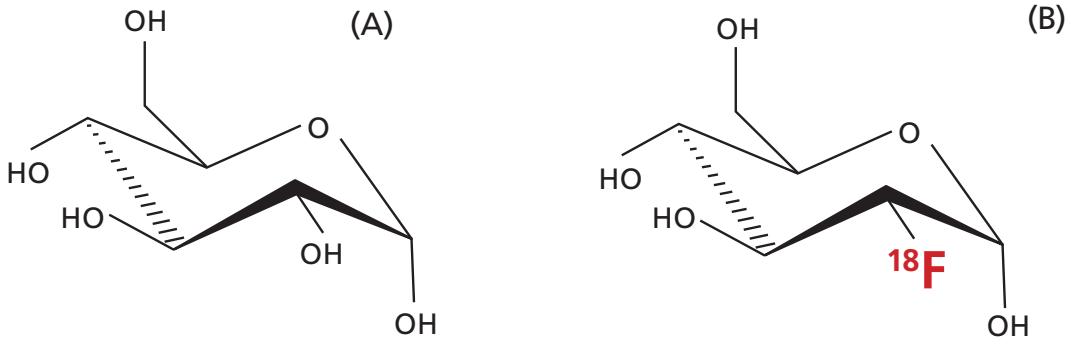
Positron Emission Tomography

Another radiodiagnostic technique is called **PET-Scan** (*Positron Emission Tomography*). When a positron-emitting radioisotope is administered to the patient, the emitted positron is annihilated upon encountering a neighboring electron, thereby generating two photons with energies of 0.511 MeV each (corresponding to the sum of the masses of one electron and one positron). The photons produced travel in opposite directions and can be detected by the scintillation chamber, normally called a **PET Scanner**.

The most commonly used radioisotope is fluorine-18. It can be incorporated into some organic molecules such as fluorodeoxyglucose (FDG), a glucose analog, with a fluorine atom replacing a hydroxyl (FIGURE III-2).

When injected intravenously into the patient, FDG tends to concentrate in organs that absorb glucose, such as the brain, which uses it in synapses; the muscles, to generate movement; in cells with faster growth, such as cancerous ones, or in inflammatory processes. The sites in which there is FDG concentration will have a more pronounced emission of photon pairs, detected by scintillators with coincidence circuit, as described in Chapter II. After the injection, the patient should remain at rest for one hour, to avoid the accumulation of FDG in the muscles, and in silence and penumbra, to avoid accumulation in the brain.

Figure III-2 – Structure of glucose (A) and fluorodeoxyglucose [^{18}F-FDG] (B)



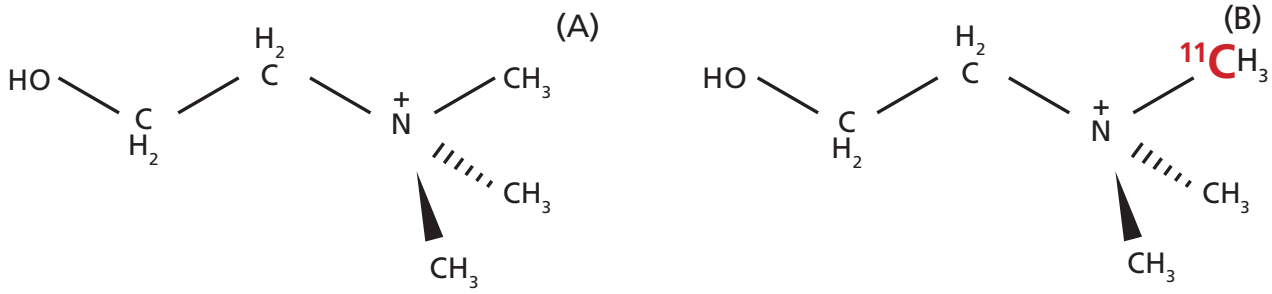
FDG is not metabolized by the body: after the decay of fluorine-18 into oxygen-18, the molecule captures a proton, thus forming "heavy" glucose (which contains oxygen-18 in the place of oxygen-16), which is metabolized in the same way as "normal" glucose. After 2 hours, 20% of the radioisotope administered is excreted through the urinary system.

Fluor-18 has a number of advantages for its use in imaging diagnostics:

- the emitted positron has a low energy level;
- there is no γ emission in the decay reaction; the only emitted photons come from electron-positron annihilation, and their energies are well defined (0.511 MeV each, corresponding to the annihilation of the two particles). This facilitates the detection of these photons.
- Fluorine-18 decays into oxygen-18, a stable and non-toxic element.

Another example of a radiopharmaceutical is C11-choline (a vitamin of the B group), in which one of the carbon-12 choline atoms is replaced by carbon-11 (FIGURE III-3). It is used for analysis of the prostate or central nervous system.

Figure III-3 Structure of the choline



(A) Structure of the choline; (B) one of the carbon-12 atoms is replaced by carbon-11, forming the ^{11}C-choline.

Treatment

Radiation therapy is used in cancer treatment through the use of γ sources external to the body (teletherapy), sources inserted directly into the site to be irradiated (brachytherapy) or radiopharmaceuticals (internal doses). Emitters of charged particles may also be used; in this case, since charged particles have a very short range, the emitters are useful in the therapy of superficial lesions, brachytherapy and as radiopharmaceuticals.

γ sources for teletherapy

Initially, cobalt-60 equipment for teletherapy was widely used. However, since the end of the 20th century, these have been replaced by linear accelerators. Although, cobalt-60 sources are still widely used in industry.

Brachytherapy

One of the most commonly used radioisotopes in brachytherapy is $^{192}_{77}\mathrm{Ir}$, in the form of fine wires made with an alloy of Ir (30%) and Pt (70%). The wire is coated with platinum or stainless steel, which shields β radiation resulting from the decay, while using only γ radiation in the treatment.

The wire is inserted into the tumor, and the γ radiation destroys the tumor cells; healthy cells, that are more distant from the γ source, are preserved.

Since the radioisotope is very dense, the wires can be small in size and yet the dose will be high. Irradiation can be performed in a few minutes, on an outpatient basis, hence the patient does not need to be hospitalized.

Radiopharmaceuticals for treatment

The iodine-131 is a β and γ emitter, administered to the patient orally as an aqueous solution of the sodium iodide salt (^{131}I-NaI). Iodine accumulates mainly in the thyroid, and β radiation can destroy benign nodules, metastases, or the remaining tissue from surgery, in the case of carcinoma. The metaiodobenzylguanidine radiopharmaceutical (^{131}I-MIBG) is used for the treatment of pheochromocytomas and neuroblastomas, which are originated by the thyroid gland and situated in the neuroendocrine system. In order to follow the evolution of the approach, the ^{131}I γ radiation is recorded by scintillographic imaging.

Sterilization of food and of hospital supplies

Sterilization of food and of hospital instruments may be performed using γ radiation, which destroys the cells of the microorganisms present in the material irradiated. As the irradiation is carried out without altering the temperature of the material, the procedure does not affect its characteristics. The sources used are accelerators (high-energy X-rays), or sources of cobalt-60 (γ rays).

Medical instruments may be irradiated inside special packs which are radiation resistant, protecting the material from further contamination prior to its use.

By applying specific doses of radiation, it is possible to eliminate microorganisms present on the food surface without modifying its characteristics. The technique has been successfully tested on grains and seasonings, which had their durability extended.

Blood for transfusion can be irradiated with cobalt-60 sources: low doses eliminate lymphocytes, which could be rejected by the patient receiving the blood; higher doses kill microorganisms, but special care must be taken not to deteriorate important blood components (e.g. by freezing the material during irradiation).

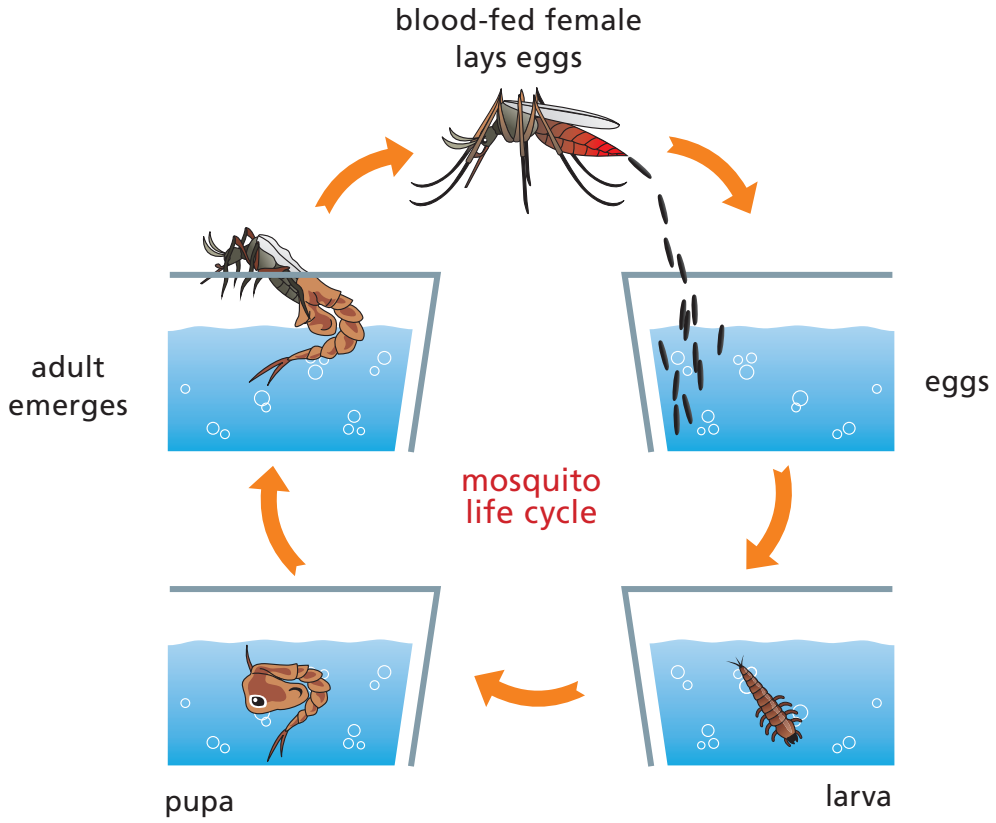
Pest control

Certain insects are pests that destroy crops or may cause disease in humans. One of the pest management methods is SIT (*Sterile Insect Technique*), which has been used for about 50 years in the control of fruit flies and tsetse flies. It is currently being tested in tropical countries for controlling the *Aedes aegypti* mosquito, which is a vector of dengue, yellow fever, chikungunya and zika viruses.

In this technique, a large number of mosquitoes are laboratory bred and raised, and the males are irradiated so that they become sterile. In the case of *Aedes aegypti*, the males are separated from the females in the pupa phase, since female pupae are larger than males, thereby making filtration a viable approach for the separation. Figure III-4 shows the stages of an insect life-cycle.

After reaching adulthood, male insects are subjected to γ radiation, which in correct doses modifies the sperm of the mosquito, making it sterile without eliminating its mating ability. Sterile males are released in nature, where they compete with wild males in mating. Females only mate once in their lifetime; therefore, by mating with a sterile male, a wild female will not breed offspring, and the mosquito population will be reduced.

Figure III-4 – Life cycle stages of a mosquito



IV - MYTHS AND FACTS ABOUT RADIOACTIVITY

Radioactivity is an atomic characteristic with which the public at large is not very familiar, and we often come upon statements which are totally or partially wrong about this subject. In this chapter, we will try to clarify some of the most common doubts.

Radioactivity first appeared during World War II: FALSE. Radioactive elements have existed on Earth ever since it was formed. The radionuclides with short half-lives have decayed over time, leaving those with a half-life greater than the age of the Earth (uranium, polonium, radium, etc.).

In nature there are also radioactive elements with shorter half-lives, which are the result, for example, of collisions between stable nuclei and particles from the solar wind. One of these elements is carbon-14, formed in the upper layers of the atmosphere when carbon-12 is bombarded; it has a half-life of 5,730 years, and is used in the dating of prehistoric fossils.

The idea that radioactivity appeared during World War II arose perhaps from the fact that the atom bomb was developed during that period, using uranium fission to generate a large amount of energy; this fission has as a byproduct a series of radioactive elements. However, radioactivity was already being used in Medicine at the beginning of the 20th century (and therefore prior to the war).

The atomic bomb was invented by Einstein: FALSE. Einstein did not work directly on the development of the atom bomb. He did propose the equation $E = Mc^2$, which, although it explains phenomena such as nuclear fission and fusion and thus provides the theoretical basis for the process, is not sufficient for the construction of a nuclear device. Fundamentally, his equation relates the concepts of mass and energy as two manifestations of the same property of matter,[28] explaining, for example, the development of energy from the fission of large nuclei (as in nuclear reactors) or through the fusion of small nuclei (as in the Sun and other stars), with the transformation of small amounts of mass into large amounts of energy.

[28] It is said that the Einstein equation is the most quoted, and least understood, equation in Physics.

Any material exposed to radiation becomes radioactive: DEPENDS. A distinction needs to be made between ionizing and non-ionizing radiation. Ionizing radiation has enough energy to ionize the atoms to which it is applied, i.e., it is able to strip electrons from these atoms. Potentially, ionizing radiation can also interact with the nuclei, whereas, non-ionizing radiation lacks sufficient energy to ionize the atoms or interact with the nuclei.

Thus, non-ionizing radiation is never capable of generating radioactive material. Examples of non-ionizing radiation are microwaves, visible light, ultraviolet or infrared radiation, and radio waves. Brief and/or slight exposures to this radiation may be beneficial, but damage may be caused if the exposure is too long or too intense (different from the one caused by ionizing radiation). These types of radiation are not able to interact with nuclei nor generate radioactive elements.

On the other hand, ionizing radiation has enough energy to strip electrons from the atoms or interact directly with the nuclei. In the latter case, unstable nuclei can be generated, which decay to a lower energy state by emitting photons or particles; however, this depends on the type of radiation, its intensity and the type of irradiated material.

Food prepared in a microwave oven becomes radioactive and can cause cancer: FALSE. Microwaves are electromagnetic waves of a longer wavelength than that of visible light (lower frequency and therefore lower energy). Therefore, it consists of non-ionizing radiation, which does not have sufficient energy to interact with the nuclei of the impacted atoms, yet interacts with certain molecules of the food by increasing their energy of vibration, thus heating the food. Along the same lines, if the microwave radiation directly impacts a person, it can cause burns.

Once it becomes radioactive, a material will be radioactive forever: FALSE. For example, if an object is irradiated with neutrons or charged particles, and some of its atoms are transformed into radioisotopes, it may be possible to make a chemical or physical extraction of the elements in question, and the rest of the object will not be radioactive. Even if this procedure is not possible, the radioactivity does not last "forever", since radioisotopes have well-defined half-lives. After 5 to 10 half-lives, it is considered that the activity of this element has ceased. It is only when the half-life of the formed element is very long that the object will remain radioactive for a long period.

A person who has suffered radiation damage can contaminate other people: DEPENDS. Radiation damage ranges from skin burns to internal lesions and changes in DNA. Lesions are not transmitted; only changes in the reproductive cells may have a damaging effect on the unborn offspring.

In general, people who have suffered radiation damage should be isolated because their immunity is lowered; it is the other people around them that can contaminate them with microorganisms against which they have no adequate defense.

When persons are contaminated by ingestion or inhalation of a radioisotope, and if it remains in their body, they will be radioactive; in this case, the people around them do need to be protected, and all secretions should be isolated for a period equivalent to 5 to 10 half-lives of the radioisotope. When the biological half-life of the element is shorter than its physical half-life, the person will be decontaminated more rapidly.

Any level of radiation is harmful to health: FALSE. Our bodies continuously receive ionizing radiation from natural sources, both on the surface of the Earth or coming from space. We are adapted to support this background radiation, which is even considered by some to be responsible for the genetic changes that have contributed to the evolution of the human being. At low doses, this radiation can be innocuous or even beneficial, as when it is used under controlled conditions as an instrument for diagnosis or treatment of various health problems. However, high doses of ionizing radiation can cause cell destruction or DNA modifications.

As for non-ionizing radiation, it can be beneficial and even necessary for the development of living beings: plants absorb visible, infrared and ultraviolet radiation in small doses to carry out photosynthesis, transforming water and carbon dioxide into organic matter; we need small doses of this same radiation from the Sun for the proper functioning of our bodies.

Ingesting non-radioactive iodine neutralizes the effects of radioactivity: DEPENDS. When ingested or inhaled, radioiodine accumulates mainly in the thyroid. Potassium iodide floods the thyroid with non-radioactive iodine and prevents the uptake of the radioactive molecules, which are subsequently excreted in the urine.

Therefore, when exposed to radioactivity such as that resulting from a nuclear power plant accident, with loss of combustible material, non-radioactive potassium iodide tablets may prevent the incorporation of the radioactive isotope into the thyroid, provided they are administered prior to the incorporation of radioactive iodine into the body.

However, radioactivity may be derived from other radioactive elements, in which case the ingestion of the tablets is useless.

People receiving the same dose of radiation suffer the same type of damage: FALSE. The damage varies from person to person, depending on several factors: age, sex, physical condition. Children are more sensitive to radiation because their organs are still under development, and some biological responses may present different intensity or time from those of an adult.

The physical condition of the individual exposed to radiation influences radiosensitivity. If a person is in good health, strong and well-nourished, his/her response to possible radiation damage will be attenuated when compared to that of a weak, undernourished and immunologically deficient person.

V - CLASSROOM ACTIVITIES

Subjects for discussion

1) Describe a case of radiation use in your daily life.
2) Describe a case of radiation use in Medicine, which you or someone you know has already experienced.
3) Can radioactivity be considered unnatural?
4) What is being done with waste from nuclear applications?
5) A radioactive substance has, initially, a number N of radioactive particles. What will be the number of radioactive particles after a half-life? And after two half-lives?

Prepare yourself to discuss these issues in the classroom; for this, carry out a previous research using the sources recommended at the end of the book, interviews with your acquaintances and family, or input from other pertinent sources.

Simulation of a radioactive decay

Physicists have discovered a new particle, called "*candyon*" for fun, and we will investigate its properties. One of these particles, dubbed "M & M", presents the interesting property that it tends to decay, that is, it tends to disappear, but in a very odd way, as we will see in the following experiment.

Materials

A large package of "M&M" chocolates[29]
A tray with raised edges

Directions

a) Obtain and count an initial amount of candies *(candyons)*. Record the count as C(0).

b) Pour the particles into a tray. When the "M & Ms" lose their energy and come to a resting state, you will notice that some of the particles are different. Some "M & Ms" have

[29] The candies can be replaced by coins.

a white "M" visible. Such particles have decayed and are now edible (eat all the "M & Ms" that have the "M" facing up).

c) Count the number of *candyons* remaining (those with the "M" facing down). Record the number as C(1).

d) Repeat steps b) and c), by changing the count number to C(2), C(3), etc., until 10 trials have been completed or until the candies are gone (if the particles run out, do not include the zero count in your data).

e) Plot the number of remaining "M&Ms" as a function of the number of trials. That is, the number of "M&Ms" will be on the y-axis (dependent variable), and the number of trials on the x-axis (independent variable).

f) The half-life of the particles is the number of trials required for half of the initial number of particles to decay. What is the half-life of the *candyons*? Compare your results with those of your colleagues, taking into account that they started with a different number of particles.

(adapted from: **Science snacks – Radioactive-decay Model** at www.exploratorium.edu - accessed on: may/ 2017 and from: **Lesson Plans, Modern Physics**, written by Lisa M Besozzi, NSF grant, Ohio Wesleyan University – not yet available on owu site)

Now let´s try another version of the experiment using other particles, calling them *dicyons*:

Materials

100 or more dice
1 tray with raised edges
1 sheet of white paperboard

Directions

a) Throw your *dicyons* on the tray. Set aside the ones that have fallen with the number 6 side up: these are the ones that have "decayed".

b) Make a column with *dicyons* that have "decayed" in the left corner of the paperboard.

c) Pick up the *dicyons* that were left on the tray, mix them and throw them again. There will be a new set fallen with the number 6 facing up.

d) Make a new column with the *dicyons* that "decayed" in item c), placing it on the right side to the first.

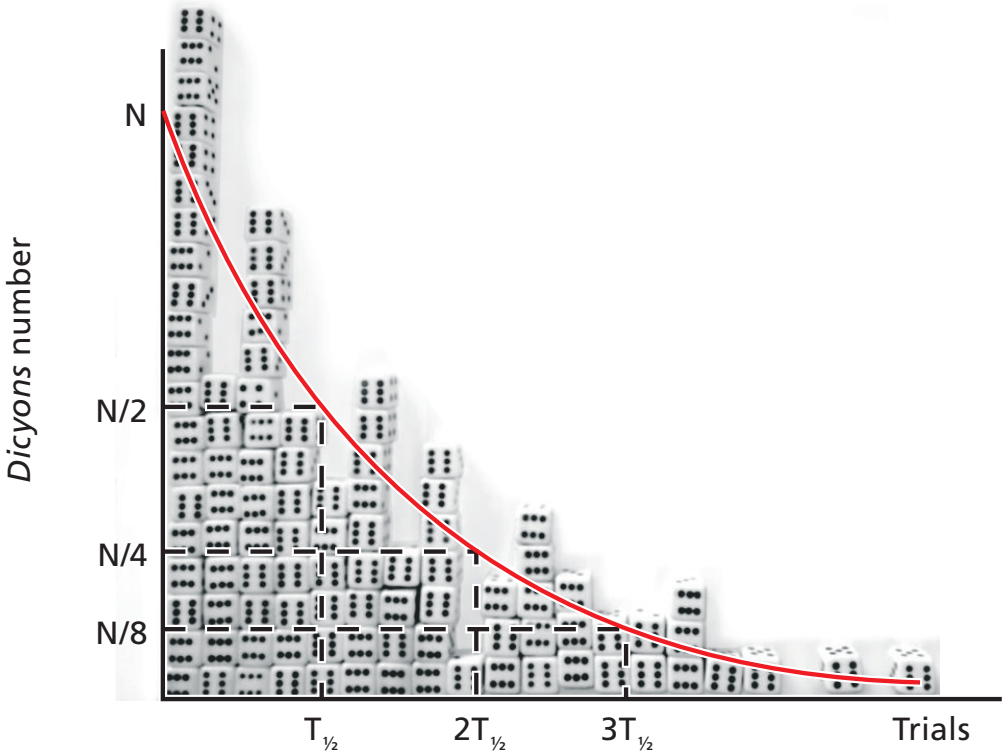
e) Repeat steps c) and d) until completing 10 columns, or until the *dicyons* all show the number 6.

f) Analyze the figure that has been formed on the paperboard: it represents the decay curve of the *dicyons*, where the number of throws is on the horizontal axis, and the number of decayed particles is on the vertical axis (FIGURE V-1).

g) Based on the figure obtained, determine the half-life of the *dicyons*. What are the similarities and differences between the decay of *candyons* and *dicyons*?[30]

[30] Note that the measured quantities are different in the two experiments: for the candies, the plotting shows the amount of "particles" that did not "decay", whereas, for the dice, the plotting shows the amount of "particles" that did "decay". The two quantities, however, follow the same decay law, so the graphs are similar. In real radioactive samples, what is measured is the number of particles that have decayed.

Figure V-1 – Dicyons decay curve



APPENDICES

A1 - Radiation units

The **activity** of a radioactive sample is measured as the number of disintegrations occurring in a given unit of time.

The historical activity unit is the curie (Ci), which expresses the activity of 1 g of the element radium (Ra):

$$1\ Ci = 3.7 \cdot 10^{10}\ s^{-1}$$

The SI unit for activity is the becquerel:

$$1\ Bq = 1\ s^{-1} = 2.7 \cdot 10^{-11}\ Ci$$

The **exposure** to a radioactive source refers to the ionization ability of this source. It is expressed as the charge produced by mass of dry air. The SI unit for exposure is given as coulombs per kilogram of air:

$$C/kg$$

The most commonly used unit is the roentgen:

$$1\ R = 2.58 \cdot 10^{-4}\ C/kg$$

The **absorbed dose** is expressed as the energy delivered by the radiation to a certain amount of mass of the absorber. The most commonly used unit is the rad (Radiation Absorbed Dose):

$$1\ rad = 0.01\ J/kg$$

The SI unit for absorbed dose is the Gray (Gy):

$$1\ Gy = 100\ rad = 1\ J/kg$$

The **equivalent dose** is the energy absorbed by a biological tissue; it takes into account the effect caused on the tissue by each type of radiation. The most commonly used unit is the rem (***R****oentgen* ***E****quivalent* ***M****an*) and is obtained by multiplying the exposure given in roentgen by a factor that depends on the type of radiation, the RBE (***R****elative* ***B****iological* ***E****fectiveness*):

$$1 \text{ rem} = 1 \text{ rad} \cdot \text{RBE}$$

The SI unit for the equivalent dose is the sievert (Sv):

$$1 \text{ Sv} = 100 \text{ rem} = 1 \text{ Gy} \cdot \text{RBE}$$

The **effective dose** takes into account the epidemiological effects due to the equivalent dose in the various organs, through a parameter w that varies for each organ of the body and is obtained from statistics of cancer incidence due to radiation. The unit for measurement of the effective dose is also the sievert.

A2 - Obtention of scintillographic images

Following the administration of a radiopharmaceutical, it accumulates in certain organs of the patient and emits radiation. The γ photons are absorbed by a crystal, which transforms its energy into visible or ultraviolet light, in a process called scintillation. The visible light then generates an electrical signal by means of a set of small photomultipliers. A computer transforms the electrical signals into the spatial coordinates x and y, related to the position of the photon emission, providing a scintillographic image, which can be used for diagnosis.

Acquisition of planar images

The scintillographic image of a patient's organ is formed by the analysis of the γ photons emitted by the accumulated radiopharmaceutical. However, part of the photons is absorbed on tissues or scattered by the Compton effect, instead of reaching the detection system. It is then necessary to use a set of collimators, small lead cylinders that allow only the photons emitted in a given direction to be collected.

The image is thus obtained by excluding a large part of the radiation emitted by the radiopharmaceutical. There is low photon density in the images because the photons absorbed or scattered by the tissues are eliminated. The geometry of the collimators has an influence on the detection efficiency of the non-scattered photons. This geometric efficiency is a function of the size of the aperture and an inverse function of the length and thickness of the collimator cylinder.

The selected γ photons then reach the **scintillating crystal**. The thickness of the crystal is important: it cannot be too thin, in order to absorb all the γ photons energy, producing visible or ultraviolet light, which will interact with the photomultipliers; at the same time, if the crystal is too thick, the photons of visible light may not reach the photomultiplier. The majority of the detectors use sodium iodide doped with thallium, NaI(Tl).

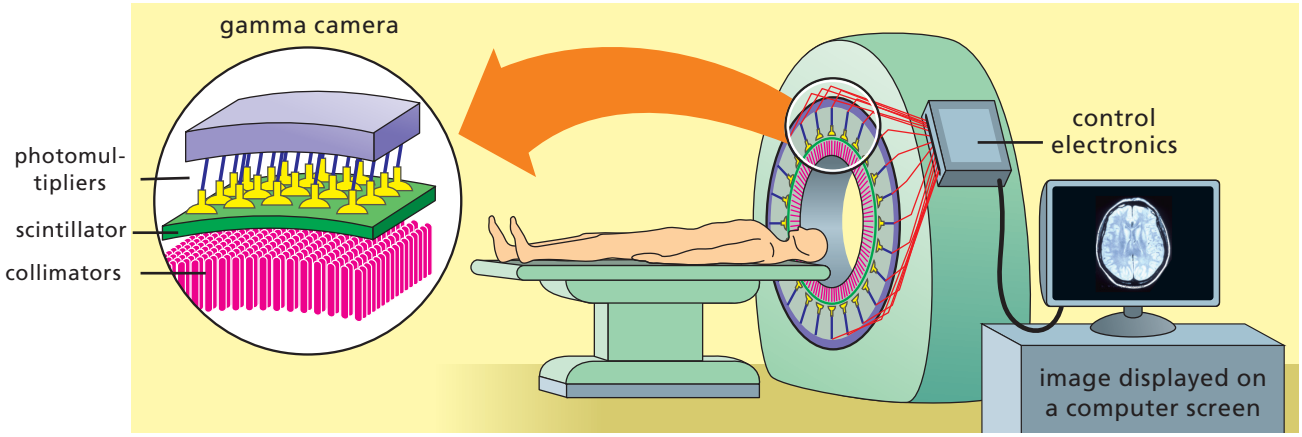
Next to the crystal are the **photomultipliers**, coupled to the crystal with optical grease, material that holds them and is transparent to the photons generated in the crystal.[31] When stimulated by a few light signals or even by β particles, they produce electrical pulses. Usually the crystal-photomultiplier assembly is known as a scintillation detector, or "detection head". The system is assembled so that there is a minimum loss due to reflection. The light falls on the photocathode, releasing low energy electrons, which are accelerated, due to an electrical potential between the photocathode and the first dynode. When colliding with the dynode, the electrons cause the release of a larger number of electrons, which accelerate to the second dynode, and so on. The electrons produced in the photomultipliers are collected as an electric pulse that can be measured by a suitable electronic circuit.

The set of collimators, scintillator crystal and photomultipliers is called the **gamma camera**.

The pulses emitted by photomultipliers are analyzed by electronic processing. The Pulse Height Analyzer (PHA) discards signals from the background, backscattered, or having a value of energy different from that stipulated by the energy window of interest, thus determining when a pulse represents a photon that should be computed in the formation of the image.

The acquisition system used for image formation is illustrated in Figure A2-1.

Figure A2-1 – Schematics of a gamma camera detection system



Based on: WAGENNAR, Douglas J. **Gamma camera basics**. Joint Program in Nuclear Medicine, March 1996. Available at: <http://www.med.harvard.edu/JPNM/physics/didactics/basics.html>. Accessed on: May 2017.

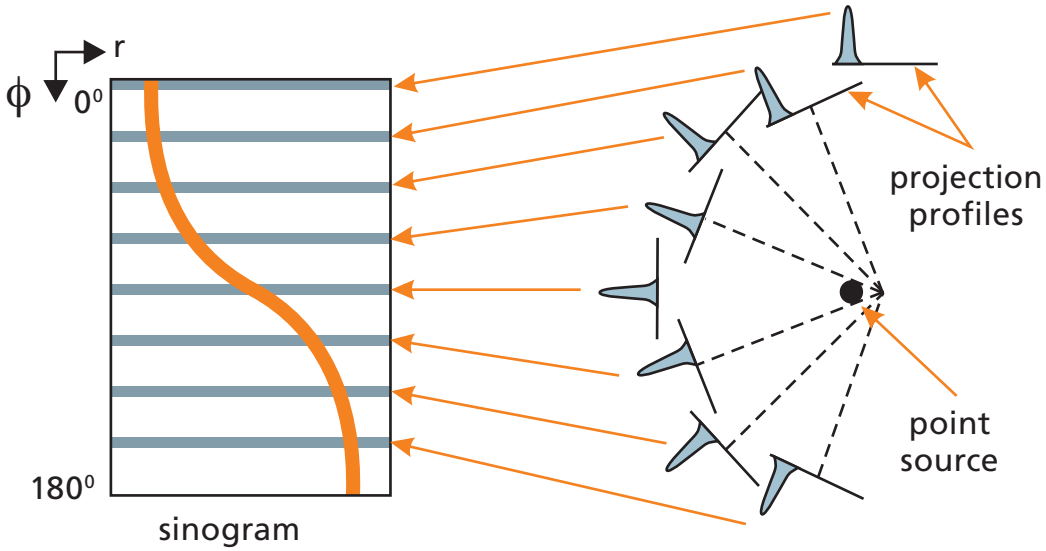
Tomographic imaging SPECT

Single-Photon Emission Computed Tomography (SPECT) is an imaging technique very similar to the planar imaging described above: it uses a gamma camera that detects the radiation emitted by the absorbed radiopharmaceutical in the organ under observation. Using this technique, however, images can be obtained in planes with different orientations, presented as cuts or reconstructed to show a 3-dimensional image.

[31] The large amount of electronic equipment raises the temperature of the examination room, that must be cooled to prevent melting and loss of optical grease.

In SPECT acquisition, the images obtained are projections from the source internal to the patient. The detection system rotates around the patient, collecting these projections and storing the information at each angle. The most known form of presentation of these projections is the sinogram, also known as Radon transform, which is a function of the intensities (counts) along the projection angles (FIGURE A2-2).

Figure A2-2 – Sinogram obtained based on the projections of a point source, with acquisitions in the range of 0° to 180°



ZANZONICO, Pat. Routine quality control of clinical nuclear medicine instrumentation: a brief review. **Journal of Nuclear Medicine**, v.49, n. 7, p.1114-1131, Jul. 2008.

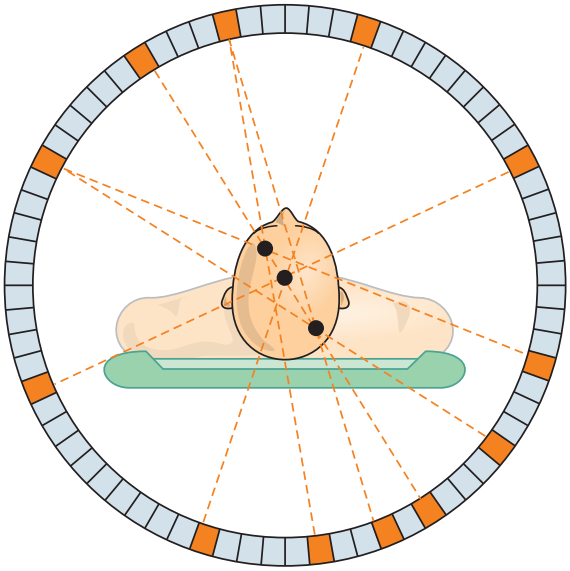
The information provided by the sinogram is used to obtain an image of the object in three anatomical planes (coronal, sagittal and axial).[32] The greater the number of projections acquired, the better and closer to the original image will be the resulting image.

Positron Emission Tomography

For Positron Emission Tomography (PET), a positron-emitting radiopharmaceutical is administered to the patient, and the γ photons from the annihilation of a positron with an electron from its vicinity are analyzed. The detection is made by a set of scintillators assembled in a ring (FIGURE A2-3). When there is annihilation, two diametrically opposite photons reach the detectors, generating an electronic signal. This occurs only if the photons move in the plane of the detector ring. Simultaneous pulses on two opposing detectors (coincidence) indicate that annihilation occurred.

[32] A coronal plane divides the body into anterior and posterior parts; a sagittal plane divides the body into right and left regions; an axial plane divides the body into upper and lower portions.

Figure A2-3 – Schematic of a detection ring for PET analysis

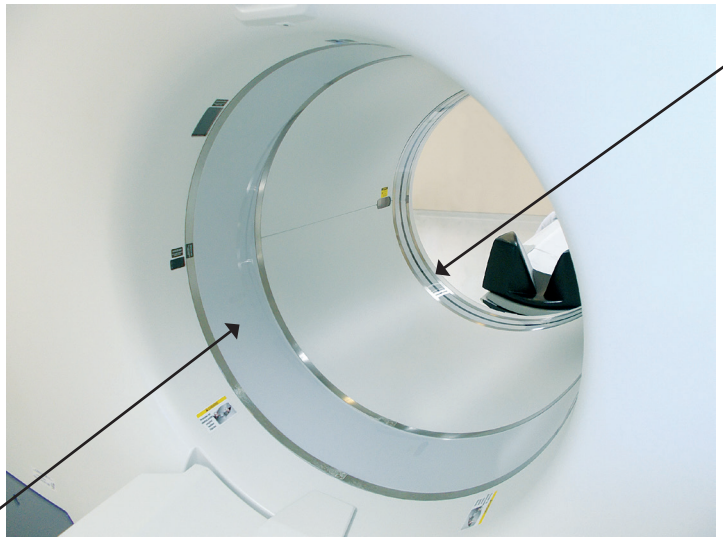


LINKS, Jonathan M. Instrumentation. in: BERNIER, Donald R.; CHRISTIAN, Paul.E.; LANGAN, James K. (ed.). **Nuclear Medicine technology and techniques**. 3. ed. St. Louis: Mosby-Year Book, Inc., 1994.

The scintillation crystals most used as detectors in PET equipment are BGO (bismuth germanate), LSO (lutetium oxyorthosilicate) and GSO (gadolinium oxyorthosilicate).

The image obtained with the PET technique can be distorted since the photons are attenuated as they pass through the patient's body. To correct this effect, the technique is combined with Computed Tomography (CT). In this technique, radiographic images of "slices" of the region of interest are obtained, which can be processed to form a three-dimensional image. The CT provides information on the density of the tissues traversed by the γ photons, and the attenuation effects can be adjusted. Figure A2-4 shows a detail of the CT-PET equipment.

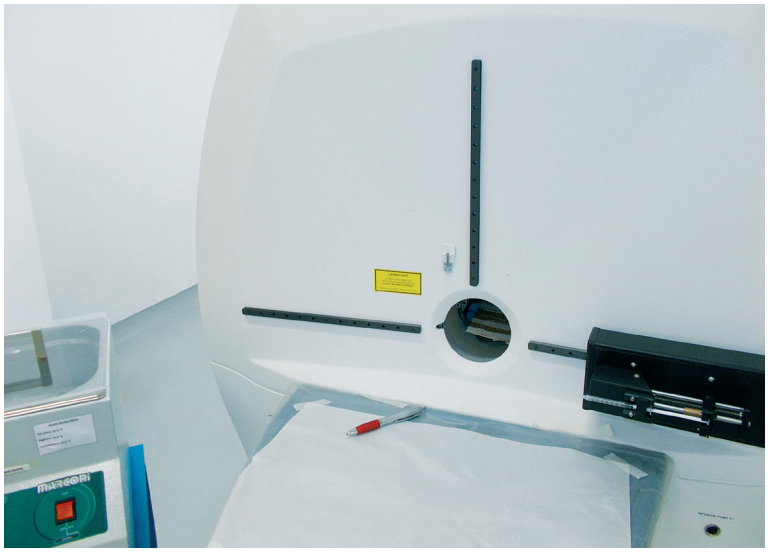
Figure A2-4 – CT-PET equipment assembly (*Faculdade de Medicina*, UFMG, Brazil)



Equipment for the research of new radiopharmaceuticals

Before approval for human use, new radiopharmaceuticals must be animal tested. Figure A2-5 shows the CT-PET equipment used for radiopharmaceutical tests in small animals.

Figure A2-5 – CT-PET equipment used for small animal tests (CDTN/CNEN, Brazil)



The pen next to the equipment gives a scale reference for its opening.

A3 - Radiation doses in medical procedures

The doses absorbed in organs can come from external irradiation (in X-ray diagnosis and therapy with linear accelerators or brachytherapy sources) or internal irradiation (with radiopharmaceuticals, both for diagnosis and therapy). When the source of irradiation is external, it is possible to verify the dose absorbed in the target organ. In the case of incorporation of radionuclides, the doses cannot be measured directly in the organs, but it is possible to estimate them based on models or on bio-dosimetrics.

Radiation doses absorbed during a medical procedure may give rise to **stochastic** or **deterministic** effects of radiation. In general, doses in diagnostic procedures are likely to cause stochastic effects, whereas in therapeutic (treatment) procedures, they may cause controlled deterministic effects. For this reason, patient protection has been emphasized by the International Atomic Energy Agency (IAEA) to ensure the safety of the procedures employed.

In every exam that uses ionizing radiation, the dose received by the patient must be taken into account, and must always be the minimum required. The health professional will evaluate the need of the test, the time that must elapse before its repetition, the dose to be administered. The use of more sensitive detectors allows the administration of lower doses, and it is important to evaluate the cost-benefit ratio for the patient.

Stochastic effects of ionizing radiation – probability proportional to dose

Stochastic effects do not have dose thresholds and occur when the cell is modified by damage to its DNA, but remains viable (i.e., capable of dividing by mitosis), and the damage eventually appears through cell proliferation. The stochastic effects of radiation are cancer after a period of latency of many years (for example, from 2 to 10 years for leukemia and 10 to 40 years for solid tumors) and severe hereditary defects. The risk of cancer depends on the irradiated tissue, and the organs and tissues which are responsible for cellular reproduction are usually more radiosensitive. These effects are strongly dependent on the age of the individual at the time of irradiation and hence on life expectancy.

To estimate the probability of stochastic effects in a given population, the **effective dose** is used. Its unit of measurement is the sievert (Sv), and 1 mSv indicates the probability of occurrence of a stochastic effect for every 100 thousand patients.

Deterministic effects of ionizing radiation - severity proportional to dose

Deterministic effects occur when there is loss of the organ or tissue function due to cell death or intracellular damage, or loss of the cells' ability to divide (mitosis). The number of affected cells increases proportionally with the radiation dose, and the functional loss of the tissue becomes evident above a **dose threshold**, which is characteristic for each type of tissue. In therapies, dose thresholds absorbed in organs or tissues may be purposely exceeded in the target tissue (tumor). Deterministic effects depend on dose rates, where lower rates allow sufficient time for recovery actions (repair mechanisms and cell repopulation). Bone marrow, gonads and eye lenses are the most sensitive tissues for deterministic effects.

Dosimetry

In terms of diagnostic procedures, the safety conditions are based on routine protocols that use dose estimates for homogeneous groups of patients, established through clinical trials. For radiopharmaceuticals, doses absorbed for each organ or tissue can be estimated using published data or directly measuring radionuclide activity in the human body, by means of Bio-dosimetry methods (collection of biological samples) or of activity quantification through of a set of images.

In the case of radiotherapy, the patient's safety and the quality of the treatment are taken into account at the same time; plans are made with complex imaging data so that the dose released in the target volume is the maximum possible while still sparing the adjacent normal tissues.

When doses cannot be measured directly, simulators are used, which represent the size and composition of the organs of adults, adolescents or children, based on anatomical studies. By means of these simulators, all the physical interactions of the radiation with the absorber can be calculated and conversion factors may be determined for the administered activity in doses absorbed in organs and tissues. These factors depend on the type of radiation, the energy emitted by interaction, the mass of the target organ and the geometry of the simulators.

The availability of data from individuals submitted to CT scans has permitted the development of three-dimensional simulators representing real individuals, not just an average individual within a hypothetical population. Advances in the technology of equipment and imaging systems have improved dosimetry methods. In this way, uncertainties in individual dose estimates can be reduced.

SUGGESTED READING

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

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

DENNAN, Suzanne; DECRISTOFORO, Clemens. (ed.). **The Radiopharmacy**: a Technologist's Guide. Vienna: European Association of Nuclear Medicine, 2008.

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.

REP, Sebastjan et. al. (ed). **Radiation Protection and Dose Optimisation**: a Technologist's Guide. Vienna: European Association of Nuclear Medicine, 2016.

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 energy and its applications:

AUSTRALIAN NUCLEAR SCIENCE AND TECHNOLOGY ORGANISATION. **Production and decay of radioisotopes**: a resource for NSW HSC chemistry and physics teachers and students. Nov. 2011. Available in: <http://ansto.gov.au/__data/assets/pdf_file/0004/63229/Production_and_Decay_of_Radioisotopes.pdf>. Accessed on: may 2017.

INTERNATIONAL ATOMIC ENERGY AGENCY. **Cyclotron produced radionuclides: principles and practice**. Vienna: IAEA, 2008. (Technical reports series, n. 465). Available in: <http://www-pub.iaea.org/MTCD/publications/PDF/trs465_web.pdf>. Accessed on: may 2017.

INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION. **Publications**. Available in: <http://www.icrp.org/publications.asp>. Accessed on: may 2017.

NUCLEAR SCIENCE WALL CHART. **Guide to the Nuclear Wall Chart**. Available in: <http://www2.lbl.gov/abc/wallchart/guide.html>. Accessed on: may 2017.

PODGORSAK, E. B. (Ed.) **Radiation oncology physics**: a handook for teachers and students. Vienna: International Atomic Energy Agency, 2005. Available in: <http:// www-pub.iaea.org/mtcd/publications/pdf/pub1196_web.pdf>. Accessed on: may 2017.

UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION. **Publications**. Available in: <http://www.unscear.org/unscear/en/publications.html>. Accessed on: may 2017.

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Silvia Maria Velasques de Oliveira holds a degree in Physics and a PhD in Biology. She is a retired researcher at the *Comissão Nacional de Energia Nuclear* (CNEN), Brazil, where she worked on the licensing, standardization and inspection of medical and industrial facilities and conducted research in Medical Physics and Individual Dosimetry She acted as a consultant to the International Atomic Energy Agency for the control of radiation sources and has given several courses to students and professionals in Brazil and abroad.

"In physical science, many of the greatest advances that have been made from the beginning of the world to the present time have been made in earnest desire to turn the knowledge of the properties of matter to some purpose useful to mankind."
(Lord Kelvin)

SBPC Sociedade Brasileira para o Progresso da Ciência

IAEA International Atomic Energy Agency
Atoms for Peace

SBBN Sociedade Brasileira de Biociências Nucleares

SBF Sociedade Brasileira de Física

CDTN Centro de Desenvolvimento da Tecnologia Nuclear

ipen Instituto de Pesquisas Energéticas e Nucleares

CNEN Comissão Nacional de Energia Nuclear

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