Radioactivity and nuclear reactions

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For the nucleus of an atom to be stable, it needs a certain proportion of neutrons and protons. Otherwise, it undergoes a series of disintegrations to reach a stable state by removing excess particles. In doing so, it emits radiation that, in high doses, attacks unprotected living tissue. Each radioactive nucleus is characterized by the nature and energy of the radiation it emits and its specific rate of decay.

1. From stable to radioactive nuclei

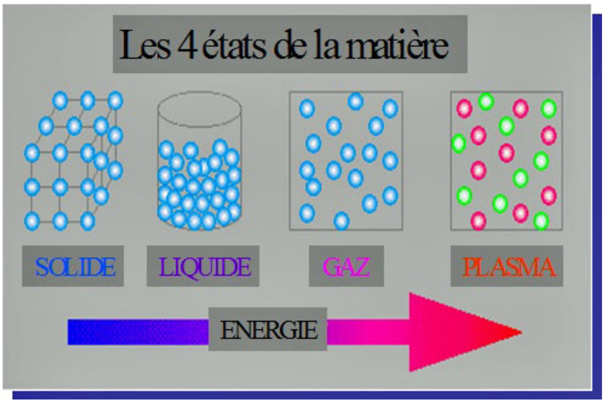

Figure 1. The 4 states of matter [Source: B. Saoutic, CEA]

Solid, liquid or gaseous matter [1] (Figure 1) is formed of **atoms**, individual or assembled into crystals and molecules. The atoms themselves are made up of a **nucleus** that contains almost all of their mass and **electrons**, very small particles with a negative electrical charge. In fact, the atom is mainly made up of emptiness: if an atom had the size of a cathedral nave, the nucleus would have that of a large drone roaring in the middle of the choir.

The nucleus is an assembly of massive particles, the **nucleons**: the mass of a nucleon is more than 1800 times the mass of an electron. Nucleons are divided between **protons** that carry a positive electrical charge and **neutrons** that are not charged. The number of protons in a nucleus determines its chemical species (1 proton = hydrogen, 2 = helium, 6 = carbon, etc.). It is the atomic number, denoted **Z**, while the total number of nucleons or **atomic mass** is denoted **A**. The atoms of the same Z whose numbers A differ are **isotopes of** the same element. Their chemical properties (linked to protons) are almost identical, but their nuclear properties can be very different. Isotopes are commonly noted by their chemical symbol preceded by their atomic mass by exposing: ^{1}H, ^{4}He, ^{12}C, ^{16}O, ^{235}U.

The electrons are distributed over **layers** more or less distant from the nucleus. **Peripheral** electrons play a major role in chemical reactions. In a molecule, atoms more or less share these peripheral electrons. An atom has the same number of protons and electrons: it is electrically neutral. If the two numbers differ, the atom is said to be ionized - but it retains the chemical nature determined by its protons. If it has an excess of electrons, it is a negative ion, or anion (example: Cl-, O--), otherwise it is a positive ion, or cation (example H+, Ca++).

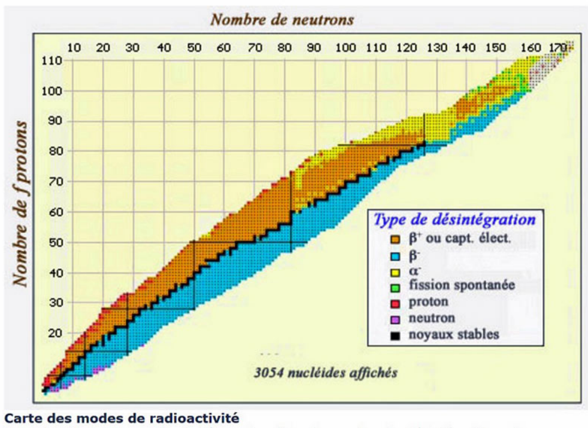

Figure 2. Stable nuclei in black (stability valley), and unstable nuclei whose color indicates the mode of disintegration.

In the nucleus, neutrons ensure the cohesion of protons that would otherwise repel each other, since they have the same electrical charge. The more nucleons in a nucleus, the more neutrons must exceed the number of protons in order for the assembly to remain **stable**: thus, the nuclei of atoms present in nature are located in what is called the "valley of stability" on a diagram comparing the number of protons and the number of neutrons in the nuclei (Figure 2).

If a nucleus has too many or too few neutrons, it is **unstable**, and will tend to reach, more or less quickly, the valley of stability, **disintegrating** according to one of the mechanisms described in the next chapter. This disintegration is accompanied by an emission of energy and radiation: this is called **radioactivity**.

Natural radioactivity is often opposed to artificial radioactivity: it is an abuse of language, there is only radioactivity, but it can come from nuclei naturally present on Earth (and in particular in the human body which naturally contains potassium ^{40}K, and carbon ^{14}C or nuclei artificially manufactured in particle accelerators or nuclear reactors. Natural radioactive elements can be derived directly from nucleosynthesis in stars and supernovæs, such as potassium ^{40}K and uranium ^{238}U. They can also be formed by the interaction of pre-existing nuclei with cosmic radiation particles, such as carbon ^{14}C. Finally, they may come from the decay of another radioactive nucleus, such as radium, which descends from uranium.

Each radioactive isotope - also known as radionuclide - is characterized by the rate of its decay. This is quantified by the **period**, sometimes called half-life, denoted **T½** , the duration after which exactly half of a given number of nuclei will have disintegrated. The period is a statistical feature: it is impossible to predict when an individual radioactive nucleus will disintegrate, but if we start from one billion of these nuclei, we know with extreme precision when only 500 million will remain. And this characteristic period of a specific nucleus can range from a fraction of a millisecond to a few billion years... (see Table 1).

Table 1: A few radioactive atoms (N=natural, A=artificial)

Nom	période	N/A	Utilisation
Tritium	12,3 ans	A	Combustible pour la fusion
Carbone 14	5730 ans	N	Datation
Oxygène 15	2,02 minutes	A	Imagerie médicale
Cobalt 60	5,27 ans	A	Gammagraphie
Césium 137	30,2 ans	A	Curiethérapie
Radon 222	3,82 jours	N	
Radium 226	1600 ans	N	
Uranium 235	704 millions ans	N	Energie nucléaire
Uranium 238	4,47 milliards ans	N	Energie nucléaire
Plutonium 239	24100 ans	A	Energie nucléaire

In the media, the period is often referred to as "lifetime" and associated comments suggest that the longer the lifetime, the more dangerous a radioactive atom is... It is exactly the opposite: if the period is long, it is because the rate of disintegration is slow, and therefore the activity is low!

2. Radiation, activity, doses

A radioactive atom tends to return to the valley of stability by emitting radiation. This can happen in different ways as shown in Figure 3.

2.1. ALPHA radiation (α)

If its nucleus is unstable because it has an excess of nucleons, which is the case for many heavy nuclei, the radioactive atom will disintegrate by ejecting an assembly of two protons and two neutrons, known as a particle α and which constitutes a helium nucleus. In doing so, the atom decreases by two atomic numbers and its atomic mass decreases by 4: plutonium ^{239}Pu thus becomes uranium ^{235}U and uranium ^{235}U becomes thorium ^{231}Th, for example.

2.2. BETA- radiation (β-)

If the radioactive atom is unstable because its nucleus has too many neutrons, a neutron will transform itself into a proton, by ejecting an electron, to keep the electrical balance, as well as a tiny particle called antineutrino (noted [latex]\overline{\nu}[/latex]). With unchanged atomic mass, the atom gains an atomic number. Thus iodine ^{135}I becomes xenon

^{135}Xe or neptunium ^{239}Np becomes plutonium ^{239}Pu: it is the radioactivity β-.

2.3. BETA+ radiation (β+)

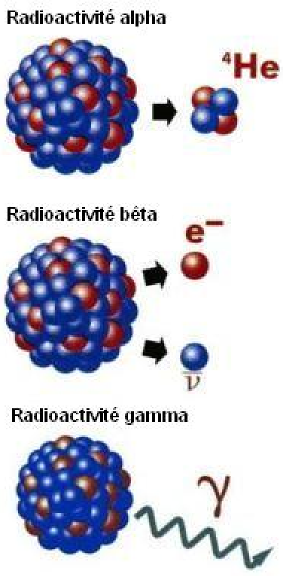

Figure 3. The main types of radioactivity[source: http://www.mesure-radioactivite.fr, IRSN, © Copyright 2010 National Network]

If the nucleus does not have enough neutrons, which is less common, a proton will transform into a neutron with emission of a positron (positive charge electron) and a neutrino. With unchanged atomic mass, the atom loses an atomic number: it is the radioactivity β+.

2.4. GAMMA radiation (γ)

Even with the correct number of nucleons, a nucleus can be excited and have to get rid of an energy excess: it does so by emitting very short wavelength electromagnetic radiation, a photon γ (Read "The colours of the sky "). A disintegration β is often associated with radiation γ.

There are rarer forms of radioactivity, corresponding, for example, to the emission of a neutron (see article "Harnessing nuclear energy", section "delayed neutrons").

After disintegration, the resulting atom can also be unstable and disintegrate: a "chain" of disintegrations occurs that only stops when stability is achieved. Thus, after 16 successive disintegrations, uranium ^{238}U becomes ^{208}Pb lead, which is stable.

2.5. Units for radioactivity

The **activity of** a radioactive atom is the rate of its disintegration. It is expressed in **becquerel** (Bq): 1 Bq = 1 disintegration per second. The becquerel is a very small unit: the natural radioactivity of the human body, mentioned in the previous chapter, is about 8000 Bq. Not enough to require wearing a lead coat to avoid irradiating your neighbours! This is why the activity of a radioactive source is often expressed in giga (billions) or even terabecquerels (thousand billion), which are GBq and TBq. The activity is a measure of rhythm, but not a measure of effect: if you are bombarded at the same rhythm with ping-pong balls or petanque balls, it will not have the same effect! Hence the notion of dose.

When radiation hits a material, it gradually loses all or part of its energy, which is absorbed by the material. The amount of energy absorbed by a given mass of matter is called the **dose**. The dose is measured in **gray** (Gy): 1 Gy = 1 joule/kg. Unlike the becquerel, the gray is a very large unit, of which the microgray (millionth) or milligray (thousandth of a Gray) submultiples are mainly used.

In living tissues (see below), radiation damage is not only dose dependent, but also depends on the nature of the radiation involved, and the nature of the tissue irradiated. If the dose is a **physical** quantity, the **equivalent dose** is a **biological** quantity that takes into account these additional parameters by multiplying the number of grays by the appropriate coefficients. It is expressed in **sievert** (Sv), more often in milli- or microsieverts (mSv, µSv).

The **dose rate** measures the absorbed dose per unit of time (examples: µSv/h, mSv/year, etc.)

3. The effects of radiation on living organisms

3.1. how to protect yourself from it

Radioactivity is frightening because radiation is not perceptible to our senses - it is invisible, odourless and silent - and because high doses can cause cancer.

If radiation is indeed beyond our senses, it is, on the other hand, easily detectable at minute doses: when we perform a "PET" examination[2], we record each individual disintegration! By comparison, none of our instruments could detect less than a few **billion billion** molecules of a chemical poison !

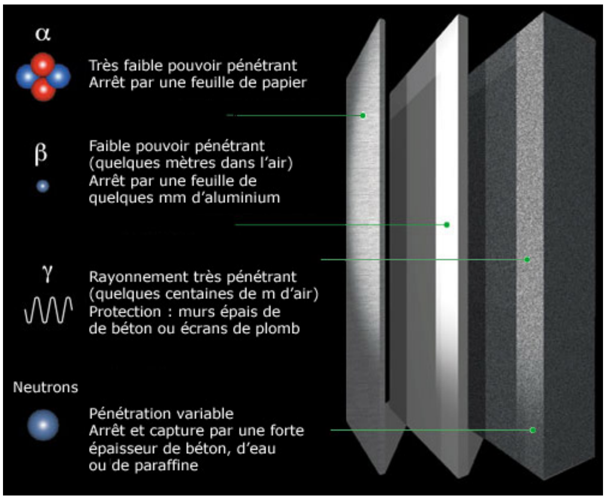

Figure 4. Penetration of different types of radiation[source: laradioactivite.com [Source : ©IN2P3)]

In addition, it is easy to protect yourself from radiation if you have located the source: first, do not approach it, if you have to approach it, do not park nearby, and finally, if your job requires you to stay close to this source, interpose a screen that will stop the radiation. As shown in Figure 4:

A sheet of cigarette paper, the small layer of dead cells in our epidermis is enough to stop alpha rays.

A few millimetres of aluminium sheet can block beta rays.

1.5 meters of concrete, or 5 meters of water will stop gammas and neutrons.

Figure 5. Osiris reactor, CEA Saclay [Source : Photo CEA]

Thus, some experimental nuclear reactors are installed at the bottom of a swimming pool (see photo Figure 5). Operators can stay above the pool, the reactor at full power: they will be less irradiated than in the open air because the water stops all the radiation from the reactor and the thick building that encloses it partially protects them from cosmic rays.

3.2. biological effects of radiation

Because of their high energy, radiation from radioactivity is able to ionize atoms (extract electrons) when they enter matter. This is why they are classified as "**ionizing radiation**", as opposed to visible light and longer wavelength electromagnetic radiation (see "The Colours of the Sky"). This ionization can break molecules and cause chemical reactions. **Cosmic rays**, energetic particles emitted by the Sun or from more distant sources, are also ionizing radiations, as well as X-rays used in medical imaging.

Most of the molecules in our body are constantly regenerated and such effects are then reversible. However, the DNA of our cells plays a particular role in carrying the memory of our genetic heritage, and its preservation is therefore essential. DNA is a huge molecule with billions of atoms arranged on two strands wrapped in a double helix: ionizing radiation can cause damage by damaging one or, worse, both strands at the same time.

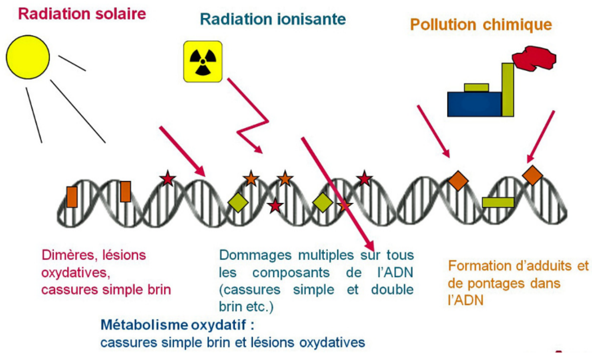

Figure 6. Different DNA stressors [Source: Dr D. Averbeck [Source : CNRS, Institut Curie) and Dr Flüry-Hérard, CEA]

But ionizing radiation is far from being the only stressors on our DNA, as illustrated in Figure 6. The main aggressor is, by far, our **metabolism**: by breathing, by digesting, we produce a lot of **free radicals**, especially oxygen, which because of their great chemical activity voraciously attack our DNA. Every cell in our body has its DNA attacked between **10,000 and 30,000 times a day** by the products of our metabolism**!**

In other words, our repair mechanisms are extremely efficient and fast. In comparison, the natural radioactivity in which we are immersed causes about a **few attacks per cell per year**.

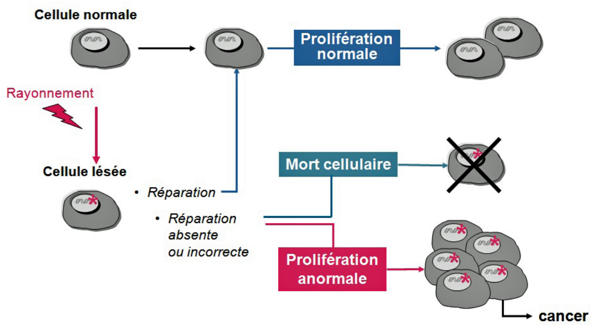

Figure 7. Different possible evolutions of a cell whose DNA is damaged [Source : CEA/ Direction des Sciences du Vivant]

What happens when our DNA is damaged? This can be seen in the diagram in Figure 7; (read "Cellular impact of solar UV"). Most of the time, the DNA is repaired and the cell continues its normal life. If the cell detects that the repair is missing or defective, in most cases it commits suicide, a mechanism called **apoptosis**, which plays an essential role in embryology [3]. If the number of destroyed cells remains low, there will be no consequences. But in rare cases, the abnormal cell starts to proliferate and this is the beginning of a cancer (which will only develop if it is sufficiently irrigated, because cancer cells are very greedy, and if it has escaped the many control mechanisms exercised by the tissue and body where it appears).

We can see that it is possible for a single irradiation to cause cancer, but the probability is extremely low.

3.3. International radiation protection rules

Created in 1955, the United Nations Scientific Committee on the Effects of Atomic Radiation (**UNSCEAR**) periodically prepares syntheses of all international scientific data in its field of competence [4]. Since its inception, UNSCEAR has carried out epidemiological studies on "cohorts", groups of individuals who have suffered significant radiation or contamination: survivors of Hiroshima and Nagasaki, workers of the Soviet Mayak complex, populations living along the Tetcha River, neighbours of the Semipalatinsk airborne atomic explosion site, American radiology personnel, aircrew (exposed to cosmic radiation during their flights), etc. It is on the basis of these studies that the rules on **radiation protection** are established, i.e. the protection of the public and workers against radioactivity. In summary, the effects of radiation are primarily a function of the dose received, but also of the "dose rate" that characterizes the intensity of that dose.

3.4. High doses

If a person receives high doses (above 1 Sv), there are many cellular deaths and the effects are visible: lesions appear on the skin, blood, intestine... these lesions are all the more serious when the dose received is high. We speak of a **deterministic** effect, and of "acute irradiation syndrome".

In addition, if a group of people receives high doses, more cancers appear in this group of people than if it had not been irradiated. The frequency varies with the dose, but the severity does not depend on it. This effect, which varies from one individual to another, is called "**stochastic**", synonymous with randomness.

3.5. Low doses

While the damage created by high doses is obvious, the low dose range is still unclear. On the one hand, cancers have many sources other than ionizing radiation, and on the other hand low doses are lost in the background noise of variations in natural radioactivity. Moreover, it is very difficult to find cohorts whose individuals differ only in the dose received: for example, very significant doses would be required to bring the cancer risk of a non-smoker to the level of the risk of a smoker! Nevertheless, we can say this:

Below 100 mSv (0.1 Sv) no observation of an increase in the number of cancers was observed, but if the irradiated and observed populations were larger, it might have been possible to observe some.

This is why the **International Commission on Radiological Protection** ICRP, in order to determine dose limits, extrapolates linearly to low doses what is observed at high doses. This assumption of a "**linear relationship without threshold**" is conservative and used according to the precautionary principle to set radiation protection rules. It may lead to overestimation of the average incidence by ignoring possible threshold effects: the repair mechanisms mentioned above may be more effective at low doses but "saturated" at high doses. In addition, the collective dose in a group of people can cover large individual variations, and the number of cancers appearing presents random fluctuations inherent in such rare events: this number approaches the average only beyond about a hundred cases.

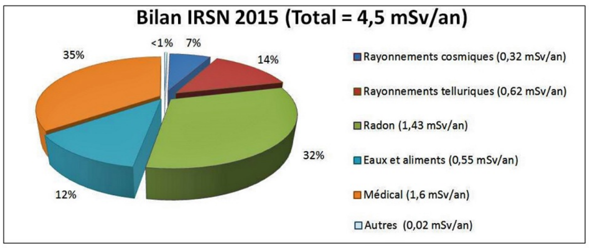

Figure 7 : Bilan de l'exposition moyenne de la population française

Figure 8. Average irradiation of a Parisian inhabitant [Source: IRSN Newsletter, September 2016]

In France, the public must not be exposed to a dose exceeding 1 mSv/year due to nuclear activities. Nuclear workers shall not be exposed to a dose exceeding 20 mSv/year.
In comparison, the dose due to natural radiation in France varies between 2.4 and 10 mSv/year, and in some regions of the world

with particularly radioactive soil, the natural dose can exceed 100 mSv/year. The average French person also receives a dose of 1 mSv/year in medical and dental radiographs. Figure 8 shows the average irradiation of a resident of the Paris basin.

3.6. Contamination

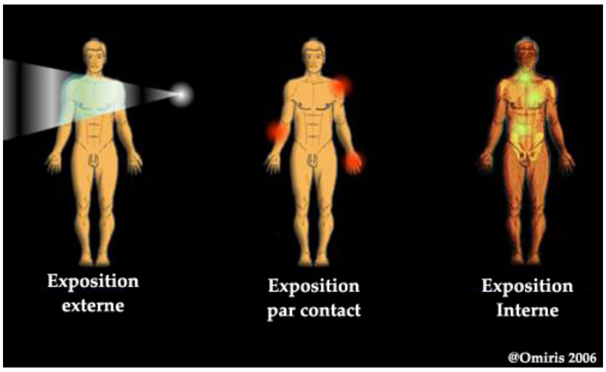

Figure 9. Three modes of radiation exposure. (a) external exposure, what counts is the duration of exposure, the distance and power of the source, the possible presence of displays. (b) Contact exposure, which is rare, results from contact with materials contaminated by radioactivity. (c) Internal exposure, the most dangerous, depends on the route of incorporation (ingestion or inhalation), the radioactive atoms, the target organ and the effective residence time of these atoms in the organ. [Source: laradioactivite.com, ©OMIRIS]

The above considerations concern irradiation or external exposure. Other exposure modes are possible as shown in Figure 9. If a radioactive element is absorbed, it is an **internal exposure** or **contamination**. There, it is no longer a question of moving away from the source or interposing a screen. Alpha rays usually stopped by a few cm of air or the thickness of the epidermis now deposit all their energy within an organ or tissue.

Internal contamination occurs in three ways: by **inhalation of** radioactive substances or dust; by **ingestion**, when they are contained in food absorbed or placed on an object placed in the mouth; by **injury** with a contaminated object or when they stain an existing wound. It is very difficult [5] to decontaminate a person who has been internally contaminated. However, its effect can sometimes be lessened, for example in the case of tritium, by drinking a lot of water.

Figure 10. Glove boxes for handling radioactive products, Mox fuel fabrication plant [Source: 102723 © LARRAYADIEU Eric / AREVA]

Nuclear workers protect themselves from contamination by wearing special clothing, gloves and masks (which will become radioactive waste). The rooms where the radioactive substances are located are sealed and the air in the rooms is replaced, which is filtered to trap radioactive dust. Highly radioactive objects are manipulated with remote manipulators through shielding or, sometimes, with robots.

For example, the manufacture of plutonium fuel follows the same steps as that of enriched uranium fuel (very weakly radioactive, read "Controlling nuclear energy"), but operations must be carried out in sealed enclosures called glove boxes (see photo Figure 10).

We cannot close this chapter without recalling the medical applications of radiation, at very high doses: radiotherapy and brachytherapy. **Radiation has cured many more cancers than it has caused.**

References and notes

Cover image. Pierre and Marie Curie, winners with Henri Becquerel of the 1903 Nobel Prize in Physics for the discovery of radioactivity.

[1] There is a fourth state of matter: plasma, which constitutes 99% of the universe. In plasma, there are no atoms: the nuclei "swim" in a sea of electrons.

[2] Positon Electron Tomography (Positon Electron Tomography) medical imaging, which allows, for example, to show the areas of the brain activated by a given activity.

[3] For example, in the formation of the hand, it is not the fingers that grow, but the spaces between the fingers that kill themselves..

[4] A summary in French of the UNSCEAR report can be found in the IRSN report 2006-74

[5] It is possible, for example, to remove inhaled plutonium particles by washing the lung with a chelating agent (special molecule in the shape of a pliers), but this is a very cumbersome procedure.

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