FROM RESEARCH TO INDUSTRY

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Communication Division
Bâtiment Saïgè - 91191 Gif-sur-Yvette cedex
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Radioactivity was not invented by man. It was discovered just over a century ago, in 1896, by the French physicist Henri Becquerel. He was attempting to find out whether the rays emitted by fluorescent uranium salts were the same as the X-rays discovered in 1895 by the German physicist Wilhelm Roentgen. He thought that the uranium salts, after being excited by light, emitted these X-rays. Imagine his surprise when, in Paris in March 1896, he discovered that photographic film had been exposed without exposure to sunlight! He concluded that uranium emitted invisible radiation, different from X-rays, spontaneously and inexhaustibly. The phenomenon he discovered was named radioactivity (from the Latin radius, meaning ray). Following Henri Becquerel’s work, in 1898 Pierre and Marie Curie isolated polonium and radium, unknown radioactive elements present in uranium ore.
Radioactivity is the transformation of an atom with the emission of rays.

**Radioactivity, a natural property of certain atoms**

In nature, the nuclei of most atoms are stable. However, certain atoms have unstable nuclei due to an excess of either protons or neutrons, or an excess of both. They are described as radioactive, and are known as radioisotopes or radionuclides. The nuclei of radioactive atoms change spontaneously into other atomic nuclei, which may or may not be radioactive. For instance, uranium-238 changes into a succession of different radioactive nuclei until it reaches a stable form, lead-206. This irreversible transformation of a radioactive atom into a different type of atom is known as disintegration. It is accompanied by the emission of different types of radiation.

A chemical element can therefore have both radioactive isotopes and non-radioactive isotopes. For example, carbon-12 is not radioactive, but carbon-14 is.

Because radioactivity only affects...
DEFINITION OF RADIOACTIVITY

“Various units are used to measure radioactivity and the effects of ionizing radiation: the becquerel, gray, sievert and curie.”

The nucleus and not the electrons, the chemical properties of radioactive isotopes are the same as those of stable isotopes.

UNITS OF MEASUREMENT OF RADIOACTIVITY
The becquerel (Bq)
What characterizes a radioactive sample is its activity, which is the number of disintegrations per second of the radioactive nuclei within it. The unit of activity is the becquerel (symbol Bq).
1 Bq = 1 disintegration per second.
This is a very small unit, so the activity of radioactive sources is more often expressed in multiples of the becquerel:
- the kilobecquerel (kBq) = 1,000 Bq,
- the megabecquerel (MBq) = 1 million Bq,
- the gigabecquerel (GBq) = 1 billion Bq,
- the terabecquerel (TBq) = 1,000 billion Bq.

The chemical properties of an atom are determined by the number of electrons it has (see The Atom booklet).

The following image symbolizes the relationship between the three units of measurement of radioactivity and the effects of ionizing radiation: a child throws objects to a friend. The number of objects thrown can be compared to the becquerel (number of disintegrations per second); the number of objects received by the friend to the gray (absorbed dose); and the marks left on the friend’s body, according to whether the objects were heavy or light, to the sievert (effect produced).

The gray (Gy)
This unit is used to measure the quantity of radiation absorbed by an organism or object exposed to radiation (the absorbed dose). The gray replaced the rad in 1986.
- 1 gray = 100 rads = 1 joule per kilo of irradiated matter.

The sievert (Sv)
The biological effects of radiation on an organism subject to exposure (depending on its nature and the organs exposed) are measured in sieverts, and are generally expressed as an “equivalent dose” and “effective dose”. The most commonly used unit is the millisievert, or thousandth of a sievert.

The curie (Ci)
The old unit of measurement of radioactivity was the curie (Ci). The curie was defined as the activity of 1 gram of radium, a natural element found in the earth with uranium. This unit is much larger than the becquerel because, in one gram of radium, 37 billion disintegrations per second are produced. So a curie is equal to 37 billion becquerels.

There are various types of detectors for detecting and measuring the radiation emitted by radioactive isotopes, including gas-filled counter tubes (proportional counter, Geiger-Müller counter, ionization chamber), scintillators coupled with photomultipliers, and semiconductors (silicon, germanium, etc.).

These detectors are extremely sensitive and commonly measure radioactivity at levels a million times lower than those that could affect our health.

RADIOACTIVE DECAY
The activity of a radioactive sample diminishes over time with the gradual disappearance of the unstable nuclei it contains. The radioactive disintegration of a particular nucleus is a random phenomenon.
“Depending on the nucleus, radioactivity can last a few seconds, several days or billions of years.”

**HALF-LIVES OF A NUMBER OF RADIOACTIVE BODIES**

<table>
<thead>
<tr>
<th>CHEMICAL ELEMENTS</th>
<th>RADIOACTIVE HALF-LIFE</th>
<th>ORIGIN</th>
<th>WHERE PRESENT</th>
<th>EXAMPLES OF USE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tritium</td>
<td>12.3 years</td>
<td>Artificial</td>
<td>–</td>
<td>Thermoneuclear fusion, Biological imaging</td>
</tr>
<tr>
<td>Carbon-11</td>
<td>20.4 minutes</td>
<td>Artificial</td>
<td>–</td>
<td>Medical imaging</td>
</tr>
<tr>
<td>Carbon-14</td>
<td>5,730 years</td>
<td>Natural</td>
<td>Atmosphere, Carbon compounds</td>
<td>Dating</td>
</tr>
<tr>
<td>Oxygen-15</td>
<td>2.02 minutes</td>
<td>Artificial</td>
<td>–</td>
<td>Medical imaging</td>
</tr>
<tr>
<td>Phosphorus-32</td>
<td>14.3 days</td>
<td>Artificial</td>
<td>–</td>
<td>Biological research</td>
</tr>
<tr>
<td>Sulphur-35</td>
<td>87.4 days</td>
<td>Artificial</td>
<td>–</td>
<td>Biological research</td>
</tr>
<tr>
<td>Potassium-40</td>
<td>1.3 billion years</td>
<td>Natural</td>
<td>Rocks rich in potassium, skeleton</td>
<td>–</td>
</tr>
<tr>
<td>Cobalt-60</td>
<td>5.27 years</td>
<td>Artificial</td>
<td>–</td>
<td>Radiotherapy, Industrial irradiation, Gamma radiography</td>
</tr>
<tr>
<td>Strontium-90</td>
<td>28.8 years</td>
<td>Artificial</td>
<td>Produced by nuclear reactors</td>
<td>Thickness gauges</td>
</tr>
<tr>
<td>Iodine-123</td>
<td>13.2 hours</td>
<td>Artificial</td>
<td>–</td>
<td>Nuclear medicine</td>
</tr>
<tr>
<td>Iodine-131</td>
<td>8.05 days</td>
<td>Artificial</td>
<td>Produced by nuclear reactors</td>
<td>Nuclear medicine (therapy)</td>
</tr>
<tr>
<td>Cesium-137</td>
<td>30.2 years</td>
<td>Artificial</td>
<td>Produced by nuclear reactors</td>
<td>Brachytherapy</td>
</tr>
<tr>
<td>Thallium-201</td>
<td>3.04 days</td>
<td>Artificial</td>
<td>–</td>
<td>Nuclear medicine</td>
</tr>
<tr>
<td>Radon-222</td>
<td>3.82 days</td>
<td>Natural</td>
<td>Gas released by granite rocks</td>
<td>–</td>
</tr>
<tr>
<td>Radium-226</td>
<td>1,600 years</td>
<td>Natural</td>
<td>Rock containing uranium</td>
<td>–</td>
</tr>
<tr>
<td>Thorium-232</td>
<td>14 billion years</td>
<td>Natural</td>
<td>–</td>
<td>Mineral dating</td>
</tr>
<tr>
<td>Uranium-235</td>
<td>704 million years</td>
<td>Natural</td>
<td>Some terrestrial rock, Granite rock</td>
<td>Nuclear deterrent Fuel</td>
</tr>
<tr>
<td>Plutonium-239</td>
<td>24,100 years</td>
<td>Artificial</td>
<td>Produced by nuclear reactors</td>
<td>Nuclear deterrent Fuel</td>
</tr>
</tbody>
</table>

However, for each radioactive isotope it is possible to give a half-life, which is the time needed for half of the radioactive atoms present at the outset to disappear by spontaneous transformation.

Depending on the radioactive nuclei concerned, this half-life varies greatly, from a few seconds or hours, or several days, to hundreds or billions of years.

**THE DIFFERENT TYPES OF DISINTEGRATION**

**Alpha radioactivity**

Alpha radiation is the emission of helium nuclei that have two protons and two neutrons. The nuclei have two positive charges.

Atoms with radioactive nuclei that have too many protons and neutrons often emit alpha radiation. They transform into another chemical element with a lighter nucleus. For example, uranium-238 is alpha radioactive and transforms into thorium-234.

**Beta minus radioactivity**

Beta minus radiation consists of negatively charged electrons.

Certain atoms with nuclei that have too high a number of neutrons emit beta minus radiation. One of the neutrons within the nucleus disintegrates into a proton plus an electron. The electron is ejected, so the atom is transformed into a different chemical element.

For example, thorium-234 is beta minus radioactive and changes into protactinium-234.
From radioelements to scientific applications

2 Radioactivity

Whether naturally or artificially, radiation is present everywhere.

**From radioelements to scientific applications**

**Beta plus radioactivity**
Beta plus radiation consists of positrons (particles with the same mass as electrons but positively charged).
Some atoms with nuclei too heavily loaded with protons emit beta plus radiation. One of the protons within the nucleus disintegrates into a neutron plus a positron. The positron is ejected, so the atom is transformed into a different chemical element. For example, iodine-122 is beta plus radioactive and transforms into tellurium-122. Note that for both types of beta disintegration, the nucleus keeps the same number of nucleons (and therefore the same mass number).

**Gamma radioactivity**
Gamma radiation is an electromagnetic wave, just like visible light or x-rays but with more energy.
This type of radiation often follows alpha or beta disintegration. After emission of the alpha or beta particle, the nucleus is still excited because its protons and neutrons are not yet in equilibrium. The excess energy is then rapidly released through the emission of gamma radiation. This is gamma radioactivity. For example, cobalt-60 transforms by beta disintegration into nickel-60, which reaches a stable state by emitting gamma radiation.

The Babyline is a device that is highly sensitive to radiation, and is used for checking waste.
NATURAL RADIOISOTOPES

When the Earth was formed, approximately 5 billion years ago, matter consisted of stable and unstable atoms. Since then, the majority of unstable atoms have disintegrated by radioactivity, and most have ended up achieving stability. However, there are still some naturally radioactive atoms:

“Natural radioactivity comes from radioelements produced in the stars billions of years ago.”

- radioisotopes characterized by a very long half-life, such as uranium-238 (4.5 billion years) and potassium-40 (1.3 billion years). These have not had enough time to disintegrate completely since they were created;
- the radioactive descendants of the above, such as radium-226, which is constantly being regenerated after the disintegration of uranium-238. Radium-226 transforms slowly into a gas, radon-222, which is itself radioactive;
- the radioisotopes created by the action of cosmic radiation on certain atomic nuclei. This is the case with carbon-14, for example, which is constantly being formed in the atmosphere.

These natural radioisotopes are present throughout the planet, in the atmosphere (carbon-14, radon-222), in the Earth’s crust (uranium-238 and uranium-235, radium-226, etc.) and in our food (potassium-40). That is why everything around us is radioactive. Since the dawn of time, the Earth and living beings have therefore been bathed in radioactivity. It was only recently (slightly more than 100 years ago), through the work of Henri Becquerel, that humans discovered they had always been living in this environment.

ARTIFICIAL RADIOISOTOPES

Artificial radioisotopes are produced using a cyclotron or nuclear reactor, for many different applications. Some radioisotopes (cobalt-60, iridium-192, etc.) can be used as sources of radiation for gamma radiography or sources of irradiation for radiotherapy or industrial applications. The use of these sources is widespread in medicine and industry (see Radiation and man booklet). Other artificial radioisotopes are created in nuclear reactors (strontium-90, cesium-137, etc.). Some are not used by man. They constitute what is known as nuclear waste.

Being highly radioactive, these radioisotopes have to be stored under high surveillance and kept isolated from humans (see The nuclear fuel cycle booklet).

“A FEW EXAMPLES OF THE ACTIVITY OF RADIOACTIVE SAMPLES FROM OUR OWN ENVIRONMENT

- Granite: 1,000 becquerels per kg.
- The human body: an individual weighing 70 kg has a radioactivity of about 6,000 becquerels, of which approximately 5,000 becquerels are due to potassium-40 (in the bones).
- Milk: 80 becquerels per liter.
- Seawater: 10 becquerels per liter.

“To meet the needs of medicine and industry, man creates artificial radioactivity.”
Radioactivity is an amazing way of exploring human beings and the environment.

Applications of radioactivity

Radioactive Tracers
Principle
The chemical properties of a radioactive isotope are identical to those of a stable isotope. The only difference is that the radioisotope is unstable. This instability causes disintegration, which translates into the emission of radiation. All we need are suitable detection tools to track these radioisotopes. For example, potassium-40, which is mixed with stable potassium in our food, follows exactly the same path within our bodies as its stable isotopes. By detecting the radiation emitted by potassium-40, we can track the movements of all potassium. A radioisotope can therefore be used as a tracer with the help of suitable detection tools. Particular molecules can also be located using the same principle. The molecules are tagged by a radioisotope, which serves as a label. Tagging can be performed in two ways: either by replacing an atom of the molecule with one of its radioactive isotopes, or by attaching a radioactive atom to the molecule. The tagged molecule then becomes a tracer.

Using radioactivity, we can track the movement of a chemical substance through the human body.

Images of the brain produced using tracers.
This method is used in medicine to monitor the action of a drug, for example, and for studying the movement of products in the environment. In these particular cases, tracers can be used in tiny quantities because radiation detection equipment is very sensitive. The effect of the radiation is not dangerous at these very low doses (see Radiation and man booklet). In addition, these isotopes have a short half-life (anything from a few minutes to a few days) so they quickly vanish from our bodies or the environment.

**Applications for tracers in medicine**

The possibilities presented by the use of tracers and radioactivity in biological research and medicine have been a key factor of the medical progress made in the 20th century. It was isotopes that, in 1943, enabled Avery to show that DNA was the basis of heredity. In the years that followed, isotopes led to the development of molecular biology, with the determination of the genetic code, the characterization of chemical reactions involved in cell function, and the understanding of energy mechanisms.

Techniques using radioactivity also increased diagnostic potential for the detection and improved treatment of diseases: this is nuclear medicine. Instead of passing radiation through the whole body, as in radiography, doctors introduce into the body a small quantity of a product tagged by a radioisotope that emits gamma radiation or beta plus radiation followed by gamma radiation. This product recognizes certain cells within the organism and indicates whether they are functioning correctly. For example, thallium-201 can be used for direct observation of the operation of the heart, to see whether it is showing signs of failure. Other types of test can detect the presence of tumors in the bones. Researchers also use nuclear medicine to understand how organs work. For example, techniques exist for direct observation of the parts of the brain involved in sight, memory, language learning and mental arithmetic.

In research, by tagging a molecule (e.g. of a drug or energy product) it is possible to monitor what happens to it in a cell or in the body. This helps with the design of drugs.

**Applications for tracers in the study of the environment**

By measuring the absorption of radiation emitted by a very small source, it is possible to determine the density of the medium through which it is traveling. This technique is used for the continuous monitoring of suspended matter in the water of rivers such as the Rhone and for regulating discharges from dams so as not to exceed levels that would endanger the river's flora and fauna. But it is also possible to track a sediment or pollutant with a radioisotope. This technique is used to optimize the route of roads and motorways in order to minimize pollution risks.
Radioactive tracers are used in industry, particularly in the petrochemicals sector.

and to check soil infiltration at waste disposal sites. Researchers also use movements of natural or artificial radioisotopes to monitor, for example, the movement of bodies of air or water.

Applications for tracers in industry
Industry uses many complex reactors with opaque walls. Radioactive tracers can be detected through these walls, so they can be used to study the behavior of fluids within these reactors. Many industries use this technique: chemistry, oil and petrochemicals, the manufacture of cement, fertilizer, paper pulp, chlorine, soda, explosives, metallurgy, energy, etc. The operation involves tagging a short burst of matter at the input to the equipment and

studying and observing the tracer concentration signal curve over time at different places (see box).

DATING
Certain natural radioactive elements can be used as chronometers for looking back in time. Methods of dating have been developed based on the decay of the radioactivity contained in the objects or remains being studied.

It is possible to go back tens of thousands of years using carbon-14, and even further using other methods such as thermoluminescence and uranium/thorium dating.

Carbon-14 dating is used to study the history of Man and his environment during a period between 5,000 and 50,000 years ago. Carbon is very widespread in our environment and in particular is a constituent of the carbon dioxide gas molecule present in the atmosphere. This carbon consists mainly of carbon-12. However a small proportion of radioactive carbon-14 is naturally present. There is the same ratio of carbon-14 to carbon-12 in the atmosphere and in the living world (plants and animals) during the life of each individual because of necessary exchanges between them (respiration, photosynthesis and food). When an organism dies, carbon-14 is no longer renewed through exchanges with the outside world. As it gradually disintegrates, the proportion contained within the organism diminishes. So by measuring the carbon-14 to carbon-12 ratio we can ascertain the date of death. The less carbon-14 there is in the fossil to be dated, the longer ago death occurred.

“Radioactivity is used to date historic and prehistoric remains.”