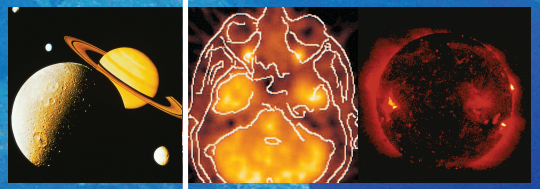
THE COLLECTION

FROM RESEARCH
TO INDUSTRY

2 → Radioactivity



DEFINITION OF RADIOACTIVITY
THE ORIGINS OF RADIOELEMENTS
APPLICATIONS OF RADIOACTIVITY

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Radioactivity

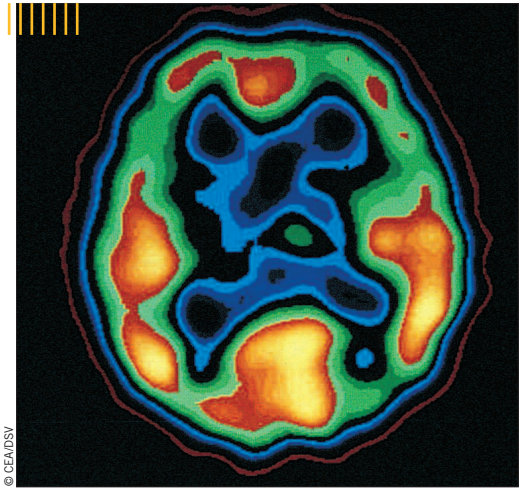

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Image of the brain obtained using positron emission tomography.

Radioactivity is used to date historic and prehistoric remains.

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From left to right: Henri Becquerel, Wilhelm Roentgen, Pierre and Marie Curie.

"Radioactivity was not invented by man. It is a natural phenomenon that was discovered at the end of the 19th century."

introduction

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.

Definition of radioactivity

RADIOACTIVITY, A NATURAL PROPERTY OF CERTAIN ATOMS

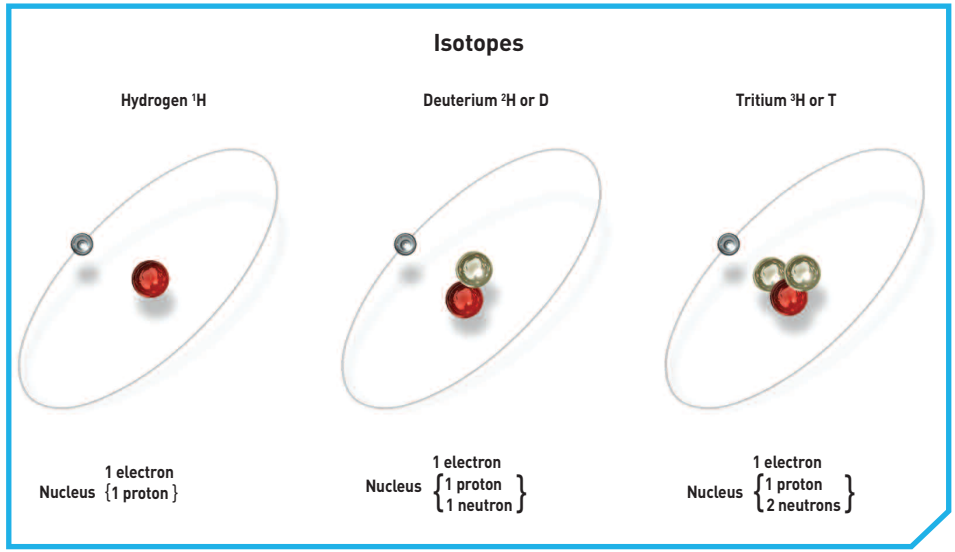
In nature, the nuclei of most atoms are stable. However, certain atoms have unstable nuclei due to an excess of either protons or neutrons, or an excess of both. They are described as radioactive, and are known as radioisotopes or radionuclides.

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.

Atoms with the same number of protons and different numbers of neutrons. They belong to the same chemical element (see *The atom* booklet). Carbon-12 (six neutrons) and carbon-14 (eight neutrons) are two carbon isotopes.

Because radioactivity only affects



"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.

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

UNITS OF MEASUREMENT OF RADIOACTIVITY

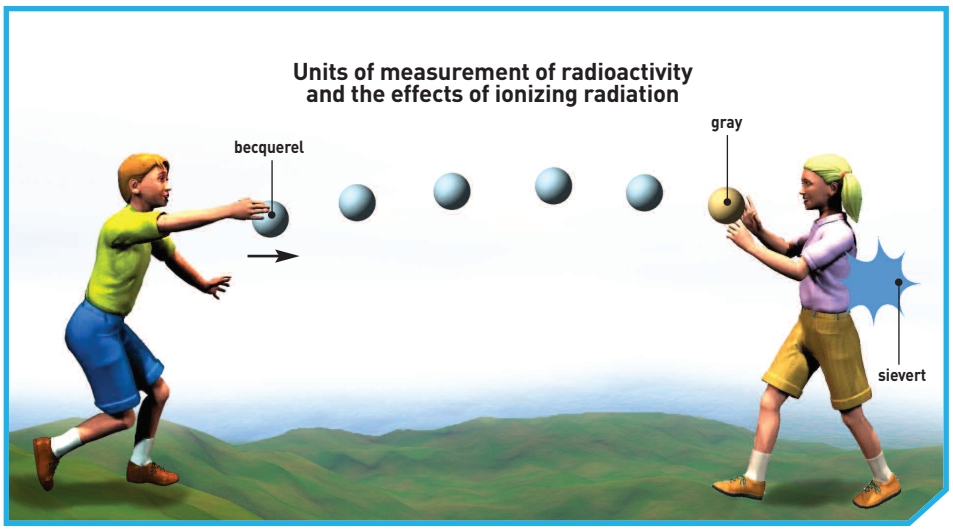
The becquerel (Bq)

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 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.

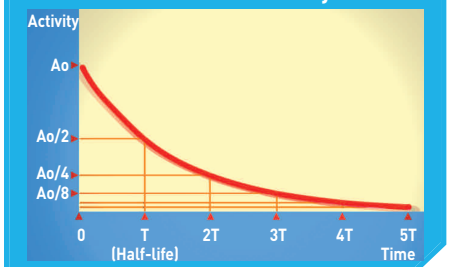
There are various types of detectors for detecting and measuring the radiation emitted by radioactive isotopes, including gas-filled counter tubes (proportional counter, Geiger-Müller counter, ionization chamber), scintillators coupled with photomultipliers, and semiconductors (silicon, germanium, etc.).

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

DECAY IN THE ACTIVITY OF A RADIOACTIVE SAMPLE OVER TIME

1 Bq = 1 disintegration per second.
As nuclei are transformed by disintegration, the radioactivity of the sample diminishes. The laws of chance, which govern radioactivity, mean that at the end of a time T, known as the half-life, the radioactivity of the sample will be halved.
At the end of two half-lives, a quarter of the radioactive nuclei of a radioelement will be left.
At the end of three half-lives, an eighth of the radioactive nuclei of a radioelement will be left.
At the end of ten half-lives, approximately a thousandth of the radioactive nuclei of a radioelement will be left.

Laws of radioactivity



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

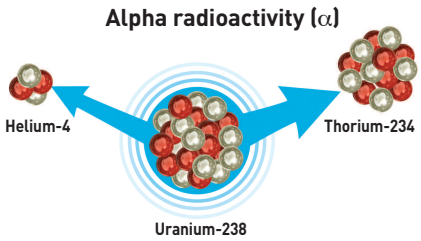
CHEMICAL ELEMENTS	RADIOACTIVE HALF-LIFE	ORIGIN	WHERE PRESENT	EXAMPLES OF USE
Tritium	12.3 years	Artificial	–	Thermonuclear fusion Biological tagging
Carbon-11	20.4 minutes	Artificial	–	Medical imaging
Carbon-14	5,730 years	Natural	Atmosphere Carbon compounds	Dating
Oxygen-15	2.02 minutes	Artificial	–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

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

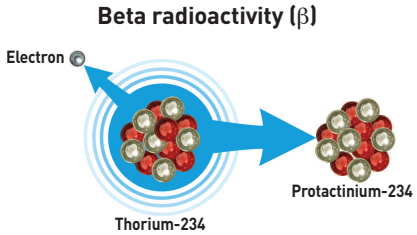
Alpha radioactivity

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.



"Radioactivity is measured as the number of disintegrations per second within a sample."

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.

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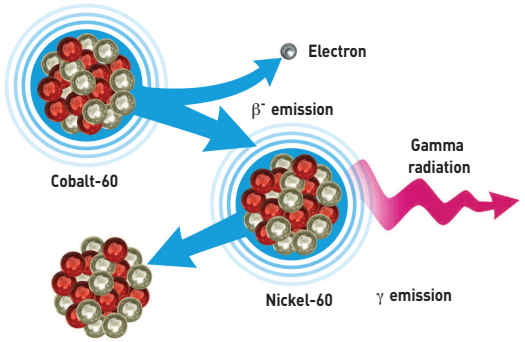
Gamma radiation (γ)



WHETHER NATURALLY OR ARTIFICIALLY, RADIATION IS PRESENT EVERYWHERE.

The origins of radioelements

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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.

Cosmic radiation continuously reaches us from the Universe; sometimes it is very strong (see *Radiation and man* booklet).

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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 8,000 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.

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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.

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Aphrodite Crouching, exposed at the Greek, Etruscan and Roman Antiquities Department of the Louvre. Gamma radiography was used to show up previous reinforcements of this marble statue and to site metal inserts and cavities accurately.

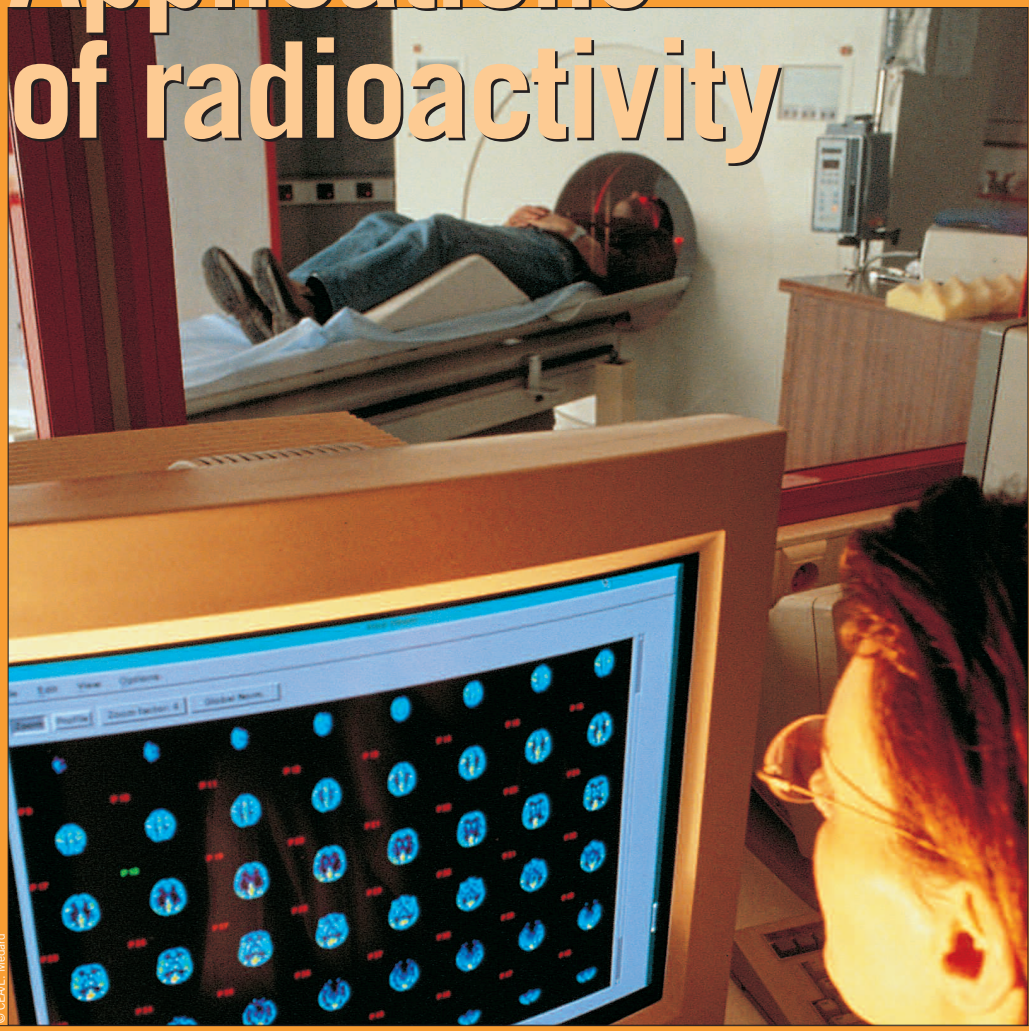
ARTIFICIAL RADIOISOTOPES

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).

"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



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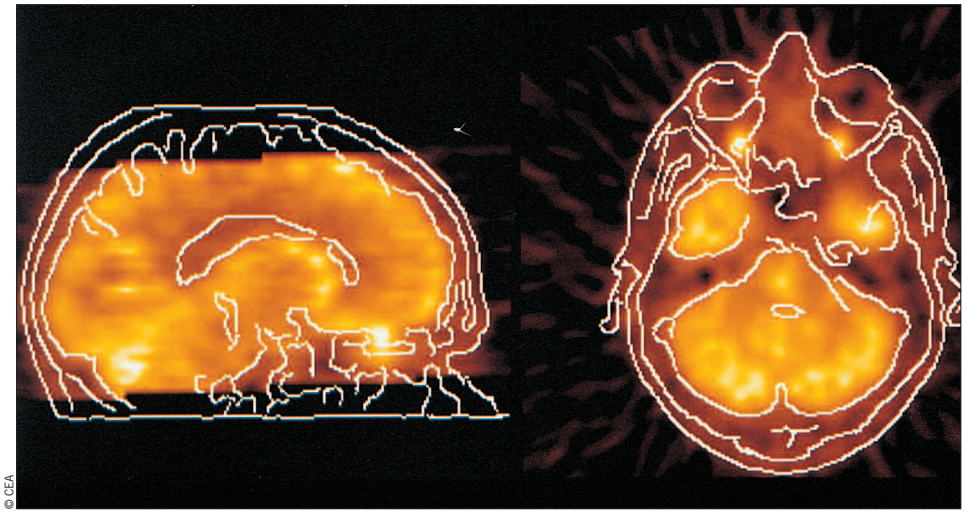
RADIOACTIVE TRACERS
Principle

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.



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Injecting radioactive tracers, used in medical imaging.

© CEA/L. Médard

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

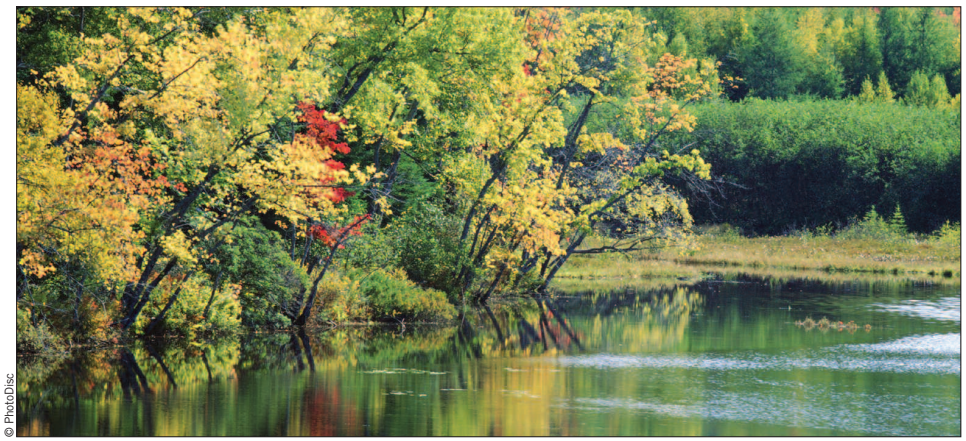
"Radioactivity enhanced biological research and medical progress throughout the 20th century."

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,

Natural and artificial radioisotopes are used as tracers for, among other things, monitoring the movement of bodies of air or water.



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Radioactive tracers are used in industry, particularly in the petrochemicals sector.

© Getty

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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).

TAGGING AS PART OF INDUSTRIAL PRODUCTION

The injection of tracers into an industrial reactor must be as brief as possible if the function recorded at the chosen measurement points is to be used as a residence time distribution for the tagged phase.

From the residence time distribution it is possible to deduce the transfer parameters of the tagged phase in the system, such as flow velocity, circulation rate, dead volume, short circuits, etc.

These measurements are used to optimize production by saving raw materials and reducing discharges into the environment.

Bison from cave paintings in Niaux (Ariège) drawn 13,000 years ago. Dated direct from the paintings using carbon-14.

© CEA

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."