# THE APPLICATION OF NUCLEAR PHYSICS IN BIOLOGY AND MEDICINE

## LA APLICACIÓN DE LA FÍSICA NUCLEAR EN BIOLOGÍA Y MEDICINA

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Many branches of modern science are related closely and cannot be isolated from each other. Physics is a fundamental natural science and has interdisciplinary links with many sciences. Fields such as medical physics, biochemistry, computa-tional biology, bioengineering, physical chemistry are a valid proof of the need for interaction between sciences [1]. In this sense, the questions about the application of Physics in Biology and Medicine have been investigated by many scholars [2–6], and new discoveries in Physics have quickly found their application in Medicine [7–9].

Biology and Medicine study living organisms. According to Davidovits, "living organisms are governed by the laws of physics on all levels" [10]. In this way, the methods of physics make it possible to study the basis of life at the molecular level. As is well known, the atoms within molecules contain nuclei around which the electrons move. Nuclear physics studies the structure and transformation of atomic nuclei. Thus, it is impossible to investigate the mechanisms of biological processes at the molecular level without using the laws of nuclear physics. The aim of this article is to present and discuss the main application areas of nuclear physics in Biology and Medicine. Properties of radioactive isotopes.

The nuclei of all atoms of a particular element have the same number of protons, but often contain different number of neutrons. Nuclei that are related in this way are called isotopes [11]. All the isotopes of a certain chemical element have the same atomic number Z but different neutron number N and mass number A. Scientists identify radioactive isotopes (or radionuclides) and stable isotopes. Radioactive isotopes can be registered by using radiation detectors because they emit radioactive radiations [12]. Stable isotopes are determined by their mass using mass spectrometers [13].

Radioactive isotopes have the following properties:

1. high energy of radioactive radiation, which allows to record small doses of a radioactive substance;
2. independence of the radioactivity from external conditions;
3. identical chemical properties of stable and radioactive isotopes of the same chemical element;
4. different types of radioactive radiation (e.g., alpha radiation, beta radiation, gamma radiation) have different permeability.

Then, the properties of radioactive isotopes determine their practical application. Stable isotopes are more difficult to register than radioactive isotopes because stable isotopes do not emit radioactive radiation.

## I. RADIOACTIVE TRACERS

Let N represent the number of radioactive nuclei present at time t. The rate of decay of the radioisotope may be written as

$$-\frac{dN}{dt} = \lambda N, \tag{1}$$

where $\lambda$ is the decay constant of the radioactive isotope. The relationship between the decay constant $\lambda$ and the half-life of radioactive isotope $T_{1/2}$ is given by formula

$$\lambda = \frac{0.693}{T_{1/2}}, \tag{2}$$

We rewrite expression 1 using formula 2 as:

$$-\frac{dN}{dt} = \frac{0.693}{T_{1/2}}N. \tag{3}$$

So, if we register 4 particles per 1 second using Geiger counter [14] then expression 3 can be rewritten as

$$4 = \frac{0.693}{T_{1/2}}N. \tag{4}$$

We can determine the number N of radioactive nuclei using expression 4:

$$N = \frac{4T_{1/2}}{0.693}. \tag{5}$$

The number $N$ of atoms in the mass $m$ of the substance is determined by the formula:

$$N = \frac{m}{M} N_A, \tag{6}$$

where $M$ is the molar mass of substance, and $N_A$ is the Avogadro constant.

The number of radioactive nuclei is equal to the number of radioactive atoms. Therefore, we can equate the corresponding parts of expressions 5 and 6, which results in:

$$\frac{0.693}{T_{1/2}} = \frac{m}{M} N_A \tag{7}$$

Using expression 7, we can determine the mass $m$ of radioactive isotope as

$$m = \frac{4T_{1/2}M}{0.693N_A}. \tag{8}$$

According to formula 8, we may calculate the numerical values for radioactive isotopes of Carbon-14 ($T_{1/2} = 5570$ years; $m_C = 2.4^{-11}$ g) and Iodine-131 ($T_{1/2} = 8.02$ days; $m_I = 8.7 \times 10^{-16}$ g). We note that the radioactive isotope with less half-life has less mass, which can be registered by a Geiger counter.

We can rewriter formula 1 using expressions 2 and 6 as

$$a = -\frac{dN}{dt}\frac{1}{m} = \frac{0.693}{T_{1/2}}\frac{N_A}{M} \tag{9}$$

where $a$ is the specific activity of a radionuclide.

According to formula 9, we can determine the specific activity of Phosphorus-32 ($T_{1/2} = 14.3$ days), which is equal to $2.9 \times 10^5$ Ci/g. For example, the specific activity of radioactive specimen equals 0.05 Ci/g. In this case, the mass of Phosphorus-32 is equal to $1.7 \times 10^{-7}$ g.

As mentioned before, the chemical properties of radioactive isotopes do not differ from the chemical properties of stable isotopes of the same chemical element. Therefore, researchers add a small amount of the radionuclide to a stable isotope of this chemical element and register it by using a radiation detector. For example, a Geiger counter registers the radionuclide Phos-phorus-32 of mass $1.7 \times 10^{-7}$ g. Thus, the radioactive radiation allows determining the transformation of the entire chemical element. Radioactive tracers have applications in many fields of science and technology.

## II. SOME USES OF ISOTOPES IN BIOLOGY

In 1923, the Hungarian scientist George de Hevesy (1885-1966) first applied the radioactive isotopes in Biology [15]. He investigated the amount of lead absorbed by plants using thorium as an indicator of lead salts. All known isotopes of thorium are unstable. The most stable one, Thorium-232, has a half-life of 14.05 billion years, and its decay ends producing the stable isotope Lead-208. If plants are burned out in different eras, the time passed from that moment can be determined by measuring the remaining thorium.

There are a number of problems in Biology that can be hardly solved without the use of isotopes. Let us present some examples.

1. A plant absorbs phosphorus from soil and fertilizers. It is necessary to determine the absorption ratio in percentage. Scientists were unable to solve this problem using analytical methods [16]. So, researchers added phosphorus fertilizers in the soil. These fertilizers contained an admixture of radioactive Phosphorus-32. After that, the researchers periodically examined the plants using a radiation detector. The intensity of radiation at different parts of the plant was determined. They determined the rate of transfer of phosphorus into the plant, distribution of phosphorus into it, etc. In this way, biologists determined the role of phosphorus in the circulation of substances in plants [17–19].

2. For a long time, scientists believed that plants absorb carbon only through leaves, and mineral salts through the roots. Experiments showed that plants assimilate carbon only under the influence of light. The use of radioactive phosphorus allowed biologists to confirm that plants feed not only through the roots, but also through the leaves [20]. Moreover, it was proved that plants are better able to absorb those substances that arrive through the leaves than those that come through the roots.

3. Radioactive tracers allowed exploring the process of photosynthesis [21,22]. Plants absorb the carbon dioxide $CO_2$ and water $H_20$, and produce oxygen $O_2$. Scientists introduced the radioisotope Carbon-14 in carbon dioxide and were able to prove that plants absorb carbon dioxide. Experiments allowed scientists to confirm that $CO_2$ flows from the roots into the leaves, where it participates in the photosynthesis together with CO2 coming from the air. Water and carbon dioxide contain oxygen. Which one contains the oxygen used by the plant? Researchers placed atoms of stable isotope Oxygen-18 into water and carbon dioxide and proved that oxygen comes only from water molecules.

4. All processes in a living organism are associated with the metabolism of substances. In this case, an animal takes a certain amino acid with food. Nitrogen is labeled with a stable isotope Nitrogen-15 in that amino acid. The amount of this isotope in different organs and in the blood of the animal was measured after a while by using mass spectrometer. This method also allows researchers to measure the time of appearance of the chemical element in different organs and its speed of movement. Radioactive tracers allow biologists to investigate the distribution of various chemical elements in different organs [23].

## III. AUTORADIOGRAPHY METHOD

In 1896, the French physicist Antoine Henri Becquerel (1852-1908) discovered the effect of radioactive radiation on a photographic plate [24]. Scientists [25–27] often apply the so-called autoradiography method with radioactive tracers. The radioactive radiation of an isotope indicator acts on the photographic film or emulsion because the photographic film or emulsion is opposed to the labeled tissue section. The distribution of blackening on the film or emulsion demonstrates the distribution of a given chemical element in an object. This created image is called an autoradiogram.

According to Barthe et al., "the scintillation gas detector is an imaging device of interest to many researchers, especially those studying the radiopharmacology" [28]. Now, the autoradiogram is available as a digital image (digital autoradiography) due to the development of scintillation gas detectors. Scientists apply this method in Medicine, Biology, Chemistry, Geology, and many other fields of science and technology. For example, the use of the autoradiography method in Biology helps to investigate the distribution of phosphorus inside a plant [29] because lighter places on the resulting photograph indicate a higher amount of radioactive phosphorus. The autoradiography method was applied successfully for the study of virus particles and nucleic acids [30].

## IV. RADIOISOTOPES IN MEDICINE

In the first place, scientists research metabolism and circulation of substances in the human body using radioactive tracers [31]. Radioisotopes in acceptable amounts are introduced into the human body with food. For example, a small amount of radioactive Sodium-24 is added in the blood. Sodium-24 is a source of gamma radiation. This radiation easily passes through the tissues of the body; therefore it is detected by detectors. The volume of blood in the human body can be determined by this method. The average adult has about 4.5 to 5.5 liters of blood circulating inside body [32]. The introduction of radionuclide Sulfur-35 in medications allows determining their ways of movement, place of accumulation, and the rate of excretion from the body. The use of radioactive tracers has made it possible to investigate the process of transforming sugar in the human body. Moreover, radioisotopes can be introduced into separate molecules [33].

In the second place, radioactive tracers are used for medical diagnosis [34]. Certain chemical elements accumulate in certain body organs. For example, phosphorus is accumulated in the bones, and radioactive Phosphorus-32 in a diseased tissue concentrates 10-100 times more than in a healthy tissue. Sargis said that "the function of the thyroid gland is to take iodine, found in many foods, and convert it into thyroid hormones: thyroxine (T4) and triiodothy-ronine (T3)" [35]. Therefore, radioactive Iodine-131 is used for diagnosis of disease of the thyroid gland because thyroid gland accumulates iodine. Doctors determine the speed of accumulation of iodine in the thyroid gland.

## V. RADIATION THERAPY

High-energy radiation kills cancer cells. Therefore, doctors apply gamma rays, X-rays, and charged particles for radiation therapy. Gamma-rays are used for killing cancerous cells in external beam radiothe-rapy because this radiation destroys cancer cells faster than healthy ones. While Radium seems the natural source of gamma-rays, it is expensive, so Cobalt-60 is often used [36]. The therapeutic installation of Cobalt-60 with radioactivity of 400 Ci replaces 400 g of radium. It is important to underline that Cobalt-60 constitutes a monochromatic gamma radiation.

Internal radiation therapy allows a higher dose of radiation in a smaller area than might be possible with external beam radiotherapy. The isotopes Phosphorus-32, Iodine-131, Gold-198, and others are used for internal radiation therapy. In this case, patients take one of these substances inside. Radioactive isotopes concentrate in the corresponding tissues of the body; they decay and operate on the desired fabric by radiation.

For example, isotopes Iodine-131 concentrate in the thyroid gland and emit beta radiation. We can write the equations of $\beta^-$ decay in this case as

$$\binom{131}{53}J \rightarrow \binom{131}{54}Xe^* + \binom{0}{-1}e + v_e^-$$

$$\binom{131}{54}Xe^* \rightarrow \binom{131}{54}Xe + \gamma$$

Notice that the second term at the right hand of the upper equation is an electron (beta particle) and the last one is an anti-neutrino; the last term in the lower equation is gamma radiation. Beta particles act on fabric of the thyroid gland. As a rule, alpha decay and beta decay include the emission of gamma-rays, which have higher energy than other electromagnetic waves. Therefore, gamma radiation is potentially harmful for the human body.

Scientists developed a method of treatment of cancer by proton beams, which called as proton therapy [37, 38]. Protons do not dissipate in the tissues of the body and stop in the cancer cells. In this way, the proton beams damage the adjacent tissues in a small extent.

## VI. WHAT IS THE MOST APPROPRIATE RADIONUCLIDE?

It is necessary to observe the safety rules when working with radioactive isotopes. The application of radioisotopes within practice involves a discussion question about regarding the risk/benefit ratio. As a rule, the radioisotopes which have the half-life in 10 times greater than the duration of the experiment are used in practice. Different radioactive isotopes have different half-lifes. Which of radioactive isotopes is safest for using in radioactive tracers?

Many radioactive isotopes are the sources of beta radiation (VI).

Table 1. Some radionuclides are used as radioactive tracers

| Radionuclide | Nuclear reaction | Half-life | Type of radiation |
|---|---|---|---|
| Carbon-11 | $(^{10}_{5})B(d,n)(^{11}_{6})C$ | 20.4 minutes | $(^{0}_{+1})e$ |
| Carbon-14 | $(^{14}_{7})N(n,p)(^{14}_{6})C$ | 5570 years | $(^{0}_{-1})e$ |
| Sodium-24 | $(^{23}_{11})Na(n,\gamma)(^{24}_{11})Na$ | 15 hour | $(^{0}_{-1})e,\gamma$ |
| Phosphorus-32 | $(^{32}_{16})S(n,p)(^{32}_{15})P$ | 14.3 days | $(^{0}_{-1})e$ |
| Sulfur-35 | $(^{35}_{17})Cl(n,p)(^{35}_{16})S$ | 87.5 days | $(^{0}_{-1})e$ |
| Cobalt-60 | $(^{59}_{27})Co(n,\gamma)(^{60}_{27})Co$ | 5.3 years | $(^{0}_{-1})e,\gamma$ |

Sargent [39] has researched the maximum energy of beta particles. Sargent's law can be written as

$$\lambda = kE_m^5 \tag{10}$$

where $\lambda$ is the decay constant, $E_m$ is the maximum energy of beta particles, and $k$ is a characteristic constant.

The decay constant is given by

$$\lambda = \ln \frac{2}{T_{1/2}} \tag{11}$$

We can rewrite Sargent's law using formula 12:

$$\frac{\ln 2}{T_{1/2}} = kE_m^5 \tag{12}$$

Expression **??** demonstrates that particles of radioactive isotopes with a longer half-life $T_{1/2}$ have less maximum kinetic energy $E_m$. It is clear that particles with low energy cause less harm to human health. For example, beta particles of Carbon-14 have low energy because a half-life of this radioactive isotope is equal to 5570 years.

## VII. CONCLUSIONS

In summary, it has been presented here a number of applications of isotopes in Biology and Medicine. The application of isotopes in Biology made it possible to investigate the mechanism of photosyn-thesis; to determine the best conditions for fertilizer application; to establish the best ways for plant nutrition; to prove the efficiency of plant nutrition through the leaves and to study the distribution of various chemical elements in different organs of animals. In the field of Medicine, the methods of nuclear physics are used for diagnosis, therapy, research of circulation of substances and medication, as well as for sterilization of medical instruments.

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