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Theme 16. Basic terms and concepts of nuclei of atoms structures theory: laws of radioactive decay and nuclear reactions; physics principles of radiometry and dosimetry

Problem

Technogenic and natural background radiation as the challenge for people

Attendance prerequisite

Note! Answer in writing to perform

1. Define or explain: nuclide, mass number, atomic number, neutron number, isotope, alpha, beta, gamma radiation, half-life, mass defect, equivalence of mass and energy, binding energy, nuclear force.

Information resources

№	Author(s)	Name of the source (textbook, manual, monograph, etc)	City, publishing house
1	R. M. Berne, M. N. Levy	Physiology	St Louis: Mosby Company, 1983
2	Vander, Sherman, Luciano	Human Physiology The Mechanisms of Body Function	New York: McGraw-Hill Book Company, 1980
3	Vander, Sherman, Luciano	Human Physiology The Mechanisms of Body Function	New York: McGraw-Hill Book Company, 1985
4	N. V. Pronina	Biological Physics The Second Module Lectures	Simferopol, 2006
5	Douglas C. Giancoli	Physics Principles with Applications	Pearson Education Limited; 7th Edition, 2016
6	Martin Hollins	Medical Physics	Tomas Nelson & Sons, 1992
7	I. Tarjan	An Introduction to Physics with Medical Orientation	Akademiai Kiado, Budapest, 1987
8	Joseph W. Kane, Morton M. Sternheim	Physics	John Wiley & Sons Third Edition, 1988
9	John Bullock, Joseph Boyle, Michael Wang	Physiology	Williams & Wilkins Third Edition, 1994

Introduction

Terms and notation. The conventional way to represent an atom of element X is $^{A}X_{Z}$, where the mass number A (or nucleon number) equals to nucleons (neutrons and protons) number in the nucleus, atomic number Z (or proton number) equals to number of protons in the nucleus.

All atoms of a particular element have the same Z, although they may contain different numbers of neutrons, giving them different values of A. Atoms with the same atomic number, but with different numbers of neutrons are called isotopes of an element. Another name for an isotope is a nuclide.

Many of elements have several naturally-occurring isotopes, but only limited number are stable (there is a negligible chance that they will decay). The rest, because their neutron-proton ratio is beyond certain limits, are unstable, or radioactive, and decay to a stable form by emission of particles and photons from the nucleus.

The radionuclide is a nuclide that spontaneously undergoes radioactive decay, by emitting either λ-, β- or γ-radiation.

Radioactive decay. Radioactive nuclei decay spontaneously. They either "go" or "don't go" randomly: the process cannot be speeded up or slowed down. Since it is a random process, the laws of statistics prevail. The more radioactive atoms there are in a sample, the greater the probability that a decay will occur in time interval. The number of nuclei that decay per second dN/dt is directly proportional to the number of radioactive nuclei N present in the sample at that time, that is: $dN/dt \sim -N$. The minus is necessary because the number of radioactive nuclei is decreasing. $dN/dt = -\lambda \cdot N$, where λ is a decay constant. This then leads to the standard equation for **radioactive decay law, namely** $\mathbf{N = N_0 \cdot e^{-\lambda t}}$, where N_0 is the original number of radioactive nuclei in the sample at time t = 0 s. The number of radioactive nuclei N remaining after a time t thus decreases exponentially.

Activity. The **activity A** of a source is the rate of decay –dN/dt of its radioactive nuclei. It is measured in becquerels (Bq). 1 Bq equals to 1 disintegration per second. The activity decreases exponentially with time $\mathbf{A = A_0 \cdot e^{-\lambda t}}$ where A_0 is the initial activity at time t = 0, and A is the activity remaining after t time.

Half-life. The **half-life** $\mathbf{T_{1/2}}$**,** of a radionuclide is defined as the average time taken for the activity to fall to half of its initial value, or alternatively as the average time taken for half the radioactive nuclei to disintegrate. After one half-life $T_{1/2}$, $A = ½A_0$ or $N = ½ N_0$. $T_{1/2} = 0.693/\lambda$. The half-life of a radionuclide is thus a constant describing how fast the material is disintegrating.

Emission of nuclear radiation. Radioactive nuclei decay by the emission of α-, β- or γ-radiation.

α-emission. An alpha particle α is identical to a helium nucleus, consisting of two protons and two neutrons. It thus carries a charge of +2e, and has a rest mass of about $7x10^{-27}$ kg. Decay by α-particle emission occurs mainly amongst nuclei of the heavier elements of atomic number greater than that of lead (Z = 82) and results in a reduction of 2 in atomic number Z and 4 in mass number A of the radionuclide.

β-emission. A β-particle can either carry a negative charge (–e) that is the familiar electron, or an equal but opposite positive charge (+e) that is a positron. It occurs basically through the transformation between neutrons and photons. In β^--decay, a neutron transforms to a proton

$$_0n^1 \longrightarrow {}_1p^1 + {}_{-1}\beta^0 + \bar{\nu}$$

neutron ⟶ proton + electron + antineutrino

Radionuclides having an access of neutrons usually decay by this mode. The neutrino and its antiparticle, the antineutrino, are particles of zero charge and approximately zero mass which carry away a certain amount of energy and momentum from such disintegration processes.

In β^+-decay, a proton transforms to neutron

$$_1p^1 \longrightarrow {}_0n^1 + {}_{+1}\beta^0 + \nu$$

proton ⟶ neutron + positron + neutrino

Neutron-deficient radionuclides often decay in this way. In such decays, the mass number A remains the same and the atomic number Z changes by 1.

γ-ray emission and metastable states. γ-rays are high energy electromagnetic radiation. They are emitted from a nucleus during transitions from an excited nuclear state to a lower energy nuclear state. Such γ-ray emission often follows another decay process such as α- or β-emission, which has left the new or daughter nucleus in an excited state. Pure γ-emission alone does not change the A or Z numbers of the nuclide. Mostly the γ-rays are emitted within a fraction of a microsecond of the primary decay, but sometimes there is a decay if the daughter nucleus is left in a metastable state. This is indicated by the symbol "m", as in the case with technetium-99m (^{99m}Tc), one of the most important radionuclides used in medicine.

Production of artificial radionuclides. Hundreds of radionuclides can be produced "artificially" by a variety of methods, most of which strive to provide a product of as high a concentration of radioactive atoms as possible. This allows the user greater flexibility since a radionuclide can always be "diluted" by the addition of inactive "carries".

The methods largely involve the bombardment of certain stable nuclei by high-energy particles such as neutrons, protons, deuterons and α-particles. The resulting nuclear reactions can lead to the formation of useful radionuclides.

Neutrons of sufficient energy to induce such nuclear reactions may be obtained in nuclear reactors and high-energy charged particles can be supplied from particle accelerators. The radionuclides so formed may then either be used directly, or provide the basis for the generators located in the hospitals themselves.

Dosimetry. Radiation can also be used to treat certain diseases, particularly cancer. It is therefore important to quantify the amount of radiation that passes through a material. This is the subject of **dosimetry.**

The strength of a source can be specified at a given time stating the source **activity** $\mathbf{A = A_0 \cdot e^{-\lambda t}}$.

The traditional unit is the **curie (Ci),** defined as 1 Ci = $3.70 \cdot 10^{10}$ disintegrations per second. The proper SI unit for source activity is the **becquerel (Bq),** defined as 1 Bq = 1 disintegration per second.

The source activity is related to the half-life, $\mathbf{T_{½}}$ by:

$$\mathbf{A = (\Delta N/\Delta t) = \lambda \cdot N = (0.693/T_{½}) \cdot N,}$$

N is the number of radioactive atoms present in the sample at that time.

Another type of measurement is the **exposure** or **absorbed dose**.

Exposure is defined as the total charge of one sign + or - produced in a unit mass of air **X = Q/m**. The unit is therefore **C/kg**. The old "CGS" unit of exposure was the **roentgen*:* 1 R** is defined as the amount of X- or γ-radiation that deposits $0.878 \cdot 10^{-2}$ J of energy per kilogram of air 1 R = $0.878 \cdot 10^{-2}$ J/kg.

The **absorbed dose** is the energy absorbed per unit mass D = E/m. The unit of absorbed dose is rad: **1 rad** is that amount of radiation which deposits 10^{-2} J/kg of any absorbing material. The proper SI unit for absorbed dose is the **gray (Gy)**: 1 Gy = 1 J/kg = 100 rad.

An exposure in air of 1 C/kg means the creation of 1/e electrons per kilogram of air, where e is the electron charge. Each of these requires the ionization energy of 34 eV, so the total energy released is 34 eV/e = 34 J/kg = 34 Gy, so for air D [Gy] = f·X [C/kg], or D [rad] = f·X [R]. In general D = f·X, where f is a conversion factor which depends on the absorbing material. The atomic number Z of soft tissue is similar to that of the air (Z of the air is 7.6, Z for muscle is 7.4), so f = 34 J/C.

When the photon energy of radiation is high, energy absorption is caused by Compton scattering which is independent of Z, therefore the relationship between exposure and absorbed dose is constant for all materials. Otherwise f varies with photon energy and the relationship can be computed with the use of graph.

Table. Radiation quality factor (QF)

Type	QF
X and γ rays	≈1
β (electrons)	≈1
Fast protons	1
Slow neutrons	≈3
Fast neutrons	Up to 10
α particles and heavy ions	Up to 20

The absorbed dose depends on the type of material absorbing the radiation. Since bone is denser than flesh and absorbs more of the radiation, the same beam passing through a human body deposits a greater dose in bone than in flesh. Equal doses of different types of radiation cause different amounts of damage. For example, 1 rad of α-radiation does 10 to 20 times the amount of damage as does 1 rad of β- or γ-rays because of greater mass. Hence ionizing collisions occur closer together so more irreparable damage is done. The **quality**

factor QF of a given type of radiation is defined as the number of rads of X- or γ-radiation that produces the same biological damage as 1 rad of the given radiation (table).

The product of the absorbed dose in rads and the QF gives a quantity known as the **effective dose H** measured in **rem: H = D·QF,** 1 rem = 1 rad·QF. The SI unit for effective dose is the sievert Sv: 1 Sv = 1 Gy·QF. By this definition, 1 rem of any type of radiation does approximately the same amount of biological damage, but corresponds to different absorbed doses.

Examples

1. The activity varies ___________________________ with the decay constant.
According to the expression $A = A_0 e^{-\lambda t}$ the activity varies exponentially with the decay constant.

2. What is the fraction of the radioactive substance that has decayed in time $\frac{1}{\lambda}$?

Given

$t = \frac{1}{\lambda}$

$\frac{N_0 - N}{N_0} - ?$

Solution

$$\frac{N_0 - N}{N_0} = \frac{N_0 - N_0 e^{-\lambda t}}{N_0} = 1 - e^{-\lambda \frac{1}{\lambda}} = 1 - e^{-1} \approx 1 - 0.37 = 0.63$$

About 63% of radioactive substance has decayed in time $\frac{1}{\lambda}$.

3. α-radiation is _____________ harmful than the flux of fast neutrons.
α-radiation is more harmful than the flux of fast neutrons, because it possesses higher quality factor.

4. A 65 kg man absorbed 0.5 Gy of X-radiation. Find the power if the dose is absorbed for 8 h.

Given

$m = 65\ kg$

$t = 8\ h$

$D = 0.5\ Gy$

$P - ?$

Solution

$$P = \frac{E}{t} = \frac{Dm}{t}$$

$$P = \frac{0.5 \cdot 65}{8 \cdot 3600} \approx 1.13 \cdot 10^{-3}\ W/m^2$$