

Ionizing Radiation and Radioactivity

[See online here](#)

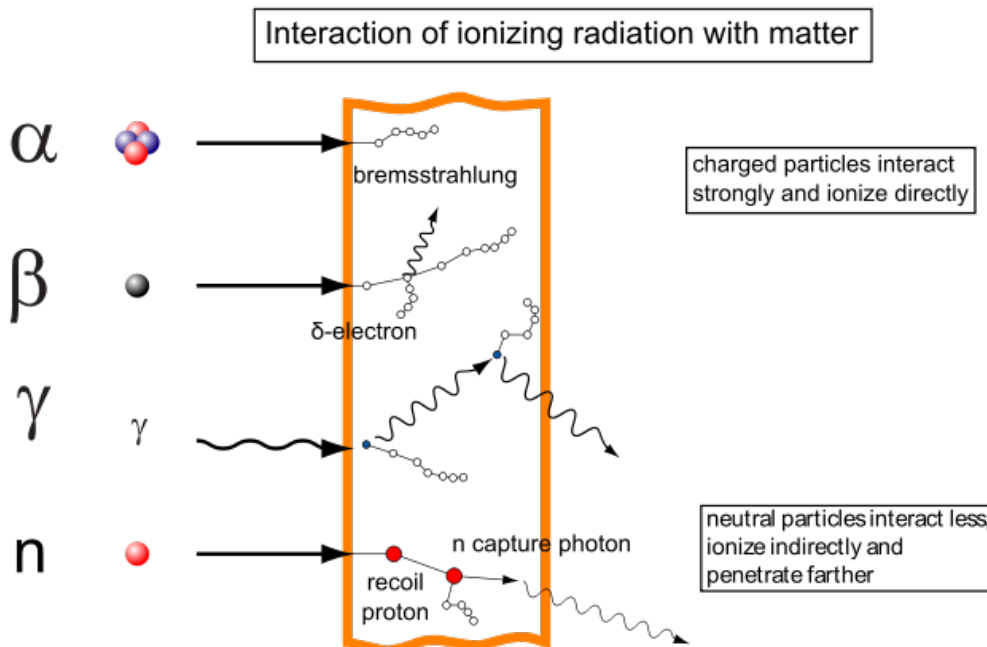
Radiation is the transfer and emission of energy in the form of waves and particles. When we speak of radiation, what is usually meant is ionizing radiation, exposure to which alters—and can kill—living body cells. Ionizing radiation is often used to kill pathogenic germs and in this way sterilize/disinfect sensitive equipment. However, as stated, it is very harmful to live cells, including the human body. Even so, with drastically reduced doses of radiation, ionizing radiation is used in radiation therapy for the treatment of cancer, e.g., in positron emission tomography. This article will equip you with exam relevant knowledge about ionizing radiation and radioactivity.



Radioactivity

In 1896, Henri Becquerel discovered a hitherto **unknown, non-continuous ray that could penetrate many materials—including black paper—and would cause fogging of photographic plates**. Two years later, a married couple, Pierre and Marie Curie, conducting experiments on uranium ore and uranium pitchblende, discovered two new elements that were particularly radioactive, namely the **elements polonium and radium**.

Radiation that carries sufficient energy to free negatively charged electrons from their atoms or molecules is known as **ionizing radiation**. What remains of the molecule are positively charged atoms. Unstable atom nuclei have the ability to transform themselves spontaneously into other atoms, the process of which results in ionizing radiation. This ability is known as radioactivity.



Picture: "Types of radiation," by Napy1kenobi. License: [CC BY-SA 3.0](https://creativecommons.org/licenses/by-sa/3.0/)

There are examples of radioactive materials that occur in nature such as the elements radium and potassium. Natural radioactivity is understood to take place when a **radionuclide tries to stabilize itself resulting in alpha, beta and gamma rays being sent out.**

Above a certain dosage, all radioactive materials, especially those that emit ionizing radiation, become a **health hazard**.

The transformation process by which the nucleus of an unstable atom loses energy via emitting radiation is known as radioactive decay. There is no way to predict when a certain atom will begin to decay, and it is not a subject of external influence.

Activity

The nuclear decay rate A (activity) is the resulting quotient number after dividing the number of decays N by the amount of time t:

$$A = dN / dt$$

Activity is measured in units of **becquerel [Bq]**. An obsolete unit is the Curie, which was named after its discoverer Marie Curie in 1896. One Curie is equivalent to 3.7×10^{10} decays per second.

If a mass is also brought into the equation, then we are talking about specific radioactivity—which is the decay per quantity of atoms of a particular radionuclide. In this case, it must be made clear which mass we are dealing with. The mass might refer to the mass of...

- ...the radionuclide only.
- ...the chemical element (isotopes included) - the chemical compound.
- ...the entire sample.

The actual activity is an important characteristic of radioactive material and is easy to calculate. If N is the number of the decaying nuclei in the substance and λ is the decay rate, then the activity of the radioactive substance can be calculated:

$$A = \lambda * N$$

Decay Constant

Every element, or more specifically, every atom, has its own particular decay constant. This is the probability of a particular type of nuclear decay and is independent of time and place.

Note: Every radionuclide has a different decay constant!

Half-Life

The amount of time required for the amount of radio active atoms to fall to half its original value is known as half-life.

$$\text{Half-life } T_{1/2} = \ln 2 / \lambda$$

In this time frame, the number N of the radioactive nuclei of an element is reduced to half of its initial value N_0 .

$$N = N_0 * (1/2)^{t/T}$$

Every radioactive isotope has its own individual half-life.

Wave Types

- **α -rays:** They are made of two protons and two neutrons bound together into a particle identical to a positively charged helium nucleus. Due to their positive charge, they can be deflected by electrical and magnetic fields. Alpha rays have a velocity of around 10^7 m/s.
- **β -rays:** These are high energy electron rays like those in cathode rays. They are made of electrons with a velocity of between 10^8 m/s and $0.99 c$. Due to their negative charge, they are deflected by electrical and magnetic fields. The rays are deflected in the opposite direction to alpha particles.
- **γ -rays:** These are high frequency electromagnetic waves with wavelengths of about 10^{-12} m and frequencies from around 10^{20} Hz. Gamma radiation is not deflected by electrical or magnetic fields.

When atoms are artificially transformed, isotopes can be left behind which emit a fourth kind of radioactive wave:

- **β^+ -rays:** They emit particles which have the same mass but opposite charge as electrons. These particles are called positrons (positive electrons).

The range of radioactive waves depends on the type of particle and on the radioactive substance itself. Alpha radiation, for example, has a low range of only 4 - 8 cm.

Absorption of radioactive waves: Alpha rays can be stopped by a sheet of paper,

while 1 mm thick aluminum plates are necessary to stop beta waves. Thick lead walls are required to absorb gamma rays.

Radioactive Decay

Today, we know that elements produce radioactive waves during their transformation into other elements. During this process, they produce large amounts of thermal energy. During elemental conversion, an atom will only ever radiate one type of ray, either alpha or beta. They are never emitted at the same time. Gamma rays, however, are typically emitted along with alpha or beta radiation.

If different radioactive materials are mixed together, like in a sample of non-pure radium, all three types of rays could be present. The following radium atom

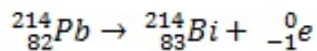
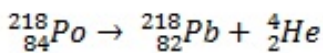
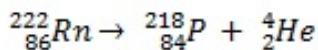
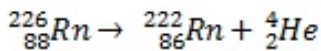


can give up a helium nucleus (i.e., alpha radiation) and be transformed into the noble gas radon:



Radon decays by emitting alpha radiation and becomes radium A. Radium A emits further alpha rays and converts into radium B. Radium B emits beta and gamma rays until it is converted into radium C. This element transformation continues leading to radium C1, radium D, radium E, etc., until the element becomes stable, i.e., no longer radioactive.

Radium A, B, C, etc., are historical names. In the following reaction equations, which is not an exhaustive list, the modern element names are used.



Atom stability: The ratio of the number of neutrons N to the number of protons Z increases proportionally to the atomic mass number. Atoms only become stable once a certain ratio of neutrons to protons is reached.

The preconditions for a stable atomic nucleus are as follows:

$$N/Z \sim 1 + 0,015 A^{2/3} \text{ with } A < 250$$

A ... mass number ($N + Z$)

N ... number of neutrons in the nucleus

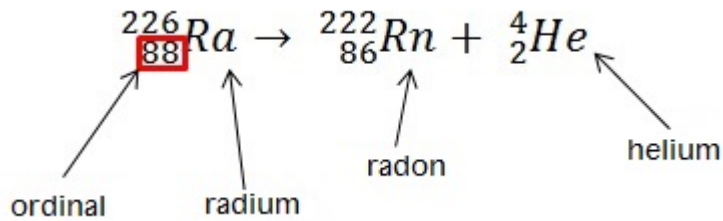
Z ... number of protons in the nucleus

α -decay

This is a type of radioactive decay that produces an atom with an atomic number that is

reduced by two.

Example:

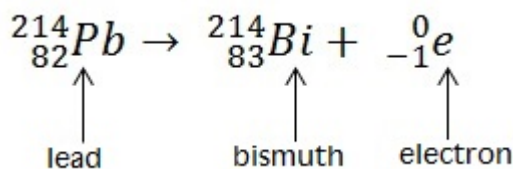


Alpha decay occurs only in nuclei that have high mass numbers.

β -decay

In this type of radioactive decay, a proton is transformed into a neutron, or vice versa, inside the atomic nucleus. The atomic nucleus is converted into a nucleus with an atomic number increased by one.

Example:



Beta-decay allows an atom to move closer to the optimal ratio of protons and neutrons. During this transformation, the nucleus emits a detectable beta particle, which is an electron or positron.

Beta-decay, in the case of a relative excess of neutrons, emits an electron when a neutron is transformed into a proton. In the case of β^+ -decay, atoms possess an excess of protons. Here, a proton is converted into a neutron while emitting a positron.

γ -decay

During gamma decay, the charge of an atom remains unchanged. Therefore, the atomic number remains the same. Gamma decay usually occurs after other forms of decay such as alpha- or beta-decay. The atomic nuclei relax from an excited state into lower-energy states.

Law of Radioactive Decay

Atom decay represents statistical behavior. Due to a large number of atoms contained in radioactive materials, it is possible to formulate laws for radioactive decay. The number of decayed nuclide atoms in a given period of time t is directly proportional to the number N_0 of existing radioactive nuclide atoms at the beginning of the period, the period itself and the decay constant of the nuclide.

$$\Delta N = \lambda * N_0 * \Delta t$$

Dosimetry

The effect radiation has on the body, or an object exposed to it is determined by the energy transferred to that body. This applies not only to radiation from radioactive substances but also for all ionizing radiations such as X-rays or neutron rays.

The absorbed dose D is calculated by the ratio of energy E that the body has received to the mass m of the body. The physical quantity of absorbed radiation is measured by the unit gray (Gy).

$$D = E / m$$

The absorbed dosage is the ratio of the dose D to time exposed.

$$D' = D / t$$

One of the principle characteristics of radiation is its ionizing effect. The number of ions present in the air is a measurement of the intensity of the radiation. The ion dose or exposure is calculated by measuring the ratio of ions in the air Q and the mass m of the irradiated air:

$$\text{ion dose } J = Q / m$$

Ion dose J generated from a given gamma-ray with the activity of 1 becquerel from a distance of 1 m per second is indicated in the specific gamma constant. The ion dose can be expressed by the corresponding energy dose, given that the required amount of energy to ionize a molecule is known for all substances.

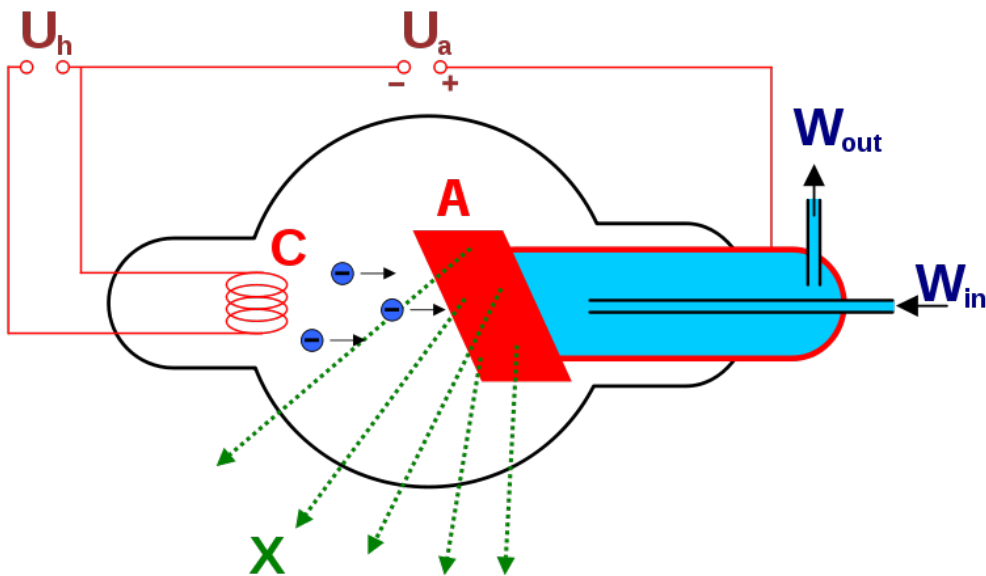
Measuring the impact of ionizing radiation on living tissue is important when dealing with radiation protection issues.

X-Rays

Wilhelm Conrad Röntgen discovered X-rays whilst working with experimental discharge tubes. He found that invisible rays can penetrate matter that is otherwise impenetrable to "normal" light. He called this kind of radiation X-rays, though some languages refer to them as Röntgen rays in honor of his name.

Electromagnetic waves with photon energy in the range 100 eV and several MeV are referred to as X-rays.

X-ray tube construction: An X-ray tube consists of a cathode (usually tungsten) inside a vacuum, which is connected to a high voltage filament. Via thermionic emission, electrons exit the cathode and are collected by an anode on the opposite side. Between the cathode and anode, a high voltage is applied, thus accelerating the electrons so that they travel from the cathode to the anode. Before the x-ray tube is **a fluorescent screen**.



Picture: "Coolidge side-window tube (scheme) C: filament/cathode (-) A: anode (+) Win and Wout: water inlet and outlet of the cooling device" by von Hmilch. License: [Public Domain](#)

Electrons exit the cathode and collide with the tungsten anode which produces photons that collect some of the kinetic energy. Invisible rays light up the fluorescent screen through a process called glass transition. The entire system must be located in a vacuum in order to function.

The amount of photon energy depends on how much energy is transferred to the photon, and this varies greatly each time. If all kinetic energy is transferred to a single photon, then it is referred to as maximum photon energy:

$$E_{\max} = E_{\text{kin}} = e * U_B$$

The amount of available energy depends on the amount of accelerating voltage U_B . That is to say, the higher the voltage the faster the electrons hit the anode and the photons thus emerge with more energy. If the heating voltage is higher, then more electrons detach themselves from the cathode.

Review Questions

Solutions can be found below the references.

1. During radioactive decay, the atomic number of the daughter nucleus in comparison to the original nucleus is rising. Therefore, it must be...

- A. ... alpha radiation.
- B. ... gamma radiation.
- C. ... the decay of an artificial radioactive substance.
- D. None of the above statements is correct.

2. The precise time of a particular ("radioactive") atomic nucleus decay ...

- A. ...is determined by the law of universal decay.
- B. ... is clearly determined by the half-life.
- C. ... depends on what atoms are present in the nucleus.
- D. ... depends on the law governing the decay of the entire atom.
- E. ... cannot be predicted.

3. A common characteristic linking the universal law of decay, the law of weakening X-rays and the Beer-Lambert law are that they all...

- A. ... represent an exponential function.
- B. ... are dependent on time.
- C. ... are dependent on the thickness of the material.
- D. ... describe a process that is invariably connected with photon radiation.
- E. ... describe the passage of radiation through matter.

References

[Endspurt Vorklinik: Physik: Die Skripten fürs Physikum](#), Thieme Verlag, 3. Auflage, 2015

[Basiswissen Physik, Chemie und Biochemie: Vom Atom bis zur Atmung – für Biologen, Mediziner und Pharmazeuten](#), Springer Verlag, 3. Auflage, 2013

[Fit fürs Abi – Oberstufenwissen](#), Schroedel Verlag, 1. Auflage, 2012

Fit fürs Abi – Oberstufenwissen, Schroedel Verlag, 1. Auflage, 2012

Correct answers: 1B, 2E, 3A

Legal Note: Unless otherwise stated, all rights reserved by Lecturio GmbH. For further legal regulations see our [legal information page](#).

Notes