Evidence and Effects of Ionizing Radiation

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Everybody is constantly exposed to small amounts of radioactive, and thus ionizing radiation. Some energy-rich radiation reaches Earth from space, slowed down by the atmosphere, but naturally radioactive substances exist here as well. In the world of medicine, radiation is used in many forms of therapy, such as X-ray exams at the dentist's office, a suspected broken bone or mammography.

Here you will find the first section of the article concerning Ionizing Radiation and Radioactivity.

Mass-energy equivalence

As early as 1905, long before the discovery of nuclear energy, the German physicist Albert Einstein inferred from his theory of relativity that **mass and energy are two manifestations of the same phenomenon**. According to his formula **$E = m*c^2$**, energy of 24 billion kilowatt hours accounts for a mass of 1 kilogram. This massive energy is stored in atomic nuclei.

The acquisition of atomic energy is thus nothing more than converting some of the mass within the nuclei into energy. This simple logic formed the foundation of radiation.

Evidence of radiation

Radioactivity can be recognized for its various effects. For instance, radiation from radioactive substances **blackens** a **light-sensitive photographic plate**. Radiation causes **flashes of light** in fluorescent materials, which is only visible with a **spinthariscope** in complete darkness.

Verification devices

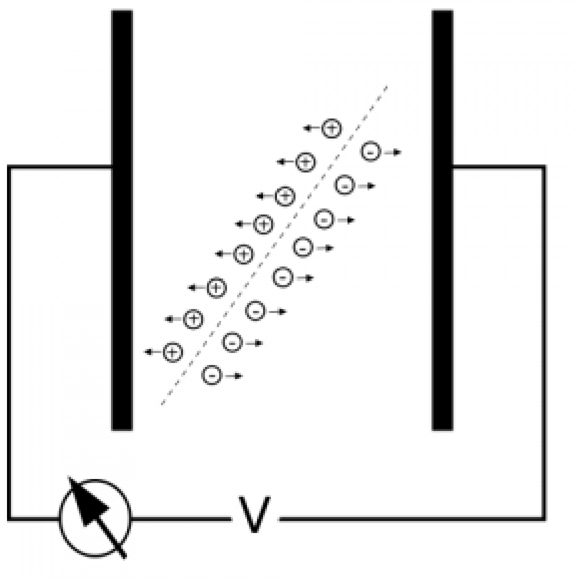


Image: "Ionisationskammer (Skizze)" by Michael Schönitzer.

Ionization chambers: The ions created between the two electrodes via impact ionization are accelerated by potential, and thus enter the inner filament where a current pulse can then be seen. However, a measurable current pulse only occurs as the result of many incidental alpha particles or correspondingly high radiation.

The Geiger-Müller counter: The Geiger-Müller counter is an ionization chamber that operates at very high voltage levels. Any incidental particle induces a measurable current pulse. The charge carriers created by impact ionization are so heavily accelerated in the strong electrical field that they release additional charge carriers in a sort of avalanche.

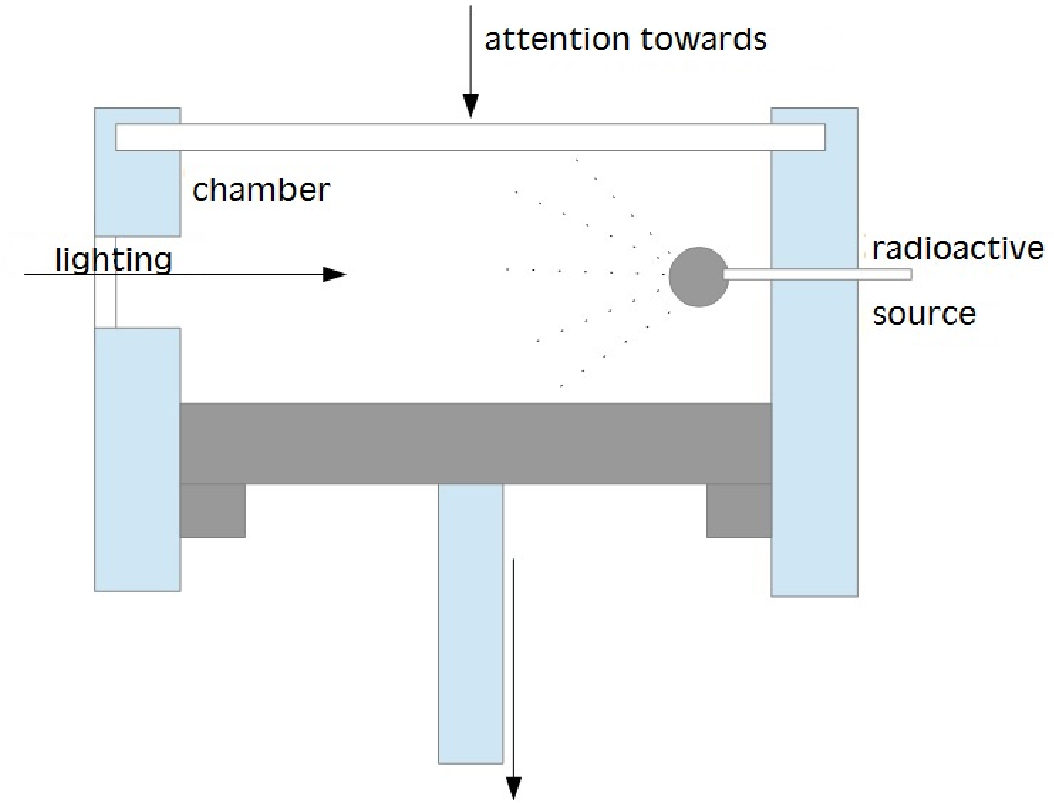
The impinging particles lead to a brief discharge pulse that can be enhanced and measured. These pulses can also be made audible in the form of crackling.

Pulse rate = Number of pulses / time

The pulse rate depends on the **activity of the radiation**, the **distance between the source of radiation and the counter** and the **design of the counter**.

The scintillation counter: The impinging radiation triggers specific luminescent materials to emit light. These flashes can be observed and counted upon magnification. The electrons emitted are then enhanced in secondary electron multipliers. This method uses the most sensitive and efficient radiation measurement device to verify the presence of radioactive substances.

The Wilson chamber: In this chamber, the air is oversaturated with water vapor. The ions created serve as condensation nuclei upon which water condensates. The resulting condenser streaks make the process of radiation/the trajectory of the particles visible.



Risks and benefits of radiation

In the field of medicine, radionuclides are frequently used in **therapy** and **diagnostics**. Compounds with a low half-life and specific characteristics are used for enrichment in organs.

Archeology and paleontology utilize **radiocarbon dating**. This process uses the half-life of the carbon isotope, which equates to 5,730 years. This carbon isotope is integrated into the organic substance of a living organism to a certain extent. Upon death of the organism, the amount of this isotope in the organism decreases. The age of materials can thus be calculated from this.

In engineering, radiation is used to **sterilize devices, refine substances** and **conserve food**, among other things.

The radiation exposure of the human body is influenced by **briefly higher and**

continuously decreasing radiation. Internal radiation is defined as the radiation of radioactive substances that enter the body via the consumption of food and respiration. These are equally distributed throughout the body or are stored in specific organs. Iodine, for example, is stored in the thyroid gland, strontium in the bone substance and radon in the lungs.

External radiation is defined as the penetration of radiation into the body. Both internal and external radiation are harmful, as ionization leads to **chemical alterations** in the body's cells, and thus to potential **changes in the genetic makeup** of the cells.

The effects of ionizing radiation on humans **depends** on the **type, energy, duration** and **temporal distribution of the radiation**, as well as the **radiation sensitivity** of the specific organ.

Heavy exposure to radiation leads to initial harm that can result in **radiation sickness** and direct **death from radiation**. Weak exposure to radiation results in long-term damage such as **cancer**. Deformities and miscarriage may also occur.

Because of the great danger of ionizing radiation of any sort, guidelines have been set by legislation. One crucial aspect includes the maximum permitted biological doses.

- **For individuals occupationally exposed to radiation:** a maximum permitted
  biological dose of 0.5 sievert/year.
- **For individuals who only occasionally come into contact with ionizing radiation:** one tenth of the values.

Decay chains

A radioactive nucleus usually forms again upon the decay of another radioactive nucleus. Natural decay chains form because the **decay products are likewise radioactive**. These decay chains lead to **stable lead isotopes** that do not decay further. Outside of decay chains, there are still many other forms of natural radioactive decay.

Example of a naturally occurring decay chain: Uranium-radium chain

- Starting nucleus: ${}_{92}^{238}U$
- Stable end nucleus: ${}_{82}^{206}Pb$

Origin of natural radioactivity

A low level of radiation from radioactive substances can be found everywhere in nature. This is referred to as the so-called **null effect**. This null effect is based on two types of constantly present forms of radiation:

1. **Cosmic radiation:** radiation from space
2. **Terrestrial radiation:** radiation from rock and construction materials.

Biological dose

The biological dose is a **measurement of the biological effect** of a form of radiation with an equal energy dose.

Biological dose = energy dose * factor of movement

The unit for the biological dose is the sievert. One sievert is equal to one joule per kilogram.

Some factors of movement q in Sv/Gy:

γ-radiation: 1
β- and X-ray radiation: 1
α-radiation: 10
Neutrons: 5 to 8
Rapid protons: 10

Artificial radioactivity

Based on the model of natural radioactivity, scientists have always attempted to convert an atom of one specific element into an atom of a different element. By bombarding the nucleus with light particles, such as protons, deuterons, neutrons and helium nuclei, this appeared possible. However, it resulted in great difficulties as the nucleus is difficult to hit and the forces holding the nucleus together are very strong.

In 1919, the English physicist Rutherford was successful in converting individual nitrogen atoms into oxygen atoms via bombardment with alpha rays in the **Wilson chamber**.

If the trails of the alpha particles in the Wilson chamber are smooth and have no kinks, then no nitrogen nucleus has been struck. If the alpha particle strikes a nucleus, the trail of the alpha particle forks off. This occurs only once in every 45,000 trails.

When branching off, the short **thick trail** shows the **path of the newly formed oxygen nucleus**, and the **long trail** shows the **path of the ejected proton**.

Rutherford converted another twelve elements using similar experiments. The energy of alpha particles is not sufficient to break down heavy nuclei. To do so, one requires particles, such as protons and deuterons, that can be brought up to another level of energy by **particle accelerators**.

The law of absorption

Nearly all applications, except for analytics, are based on the various types of absorption of radiation, such as X-rays, computer tomography, and so on.

The degree of absorption is conveyed by radiographic film or suitable detectors. Factors necessary for the absorption of radiation, especially for radioactive rays, include:

- Diameter D of the screened layers
- Texture of the layers
- Extent of the radiation’s energy
- Type of radiation.

A weakening of radiation, especially X-ray radiation, occurs through **ionization** (photo effect) or scattering processes.

Note: The Law of Absorption states that gamma radiation is exponentially weakened via absorption by a material positioned between the radioactive source and the recipient.

Safety measures for X-ray equipment in medicine

The most important safety measures for lowering patients’ exposure to radiation during X-ray treatment is **keeping them at a greater distance** to the source of radiation. This not only applies to the distance from the focus of the tubes, but also to the distance from the useful beam field in the air and the patient’s volume located in the useful beam, which emits intensive stray radiation.

One cause for the decrease in intensity upon increasing the distance lies in **more frequent interaction between the photons in the air**. The resulting weakening, however, is generally insignificant and only amounts to 5 % of the useful radiation in the air for 100 kV tube voltage and 2 mm AI total filtration, for example.

The law of distance applies: Radiation emitted from a roughly point-shaped source loses intensity inverse to the square of the distance of the source of the emitter from the source, as the simultaneously emitted, radioactive particles are distributed homogenously onto a surface increasing in distance.

Lead equivalent

The lead equivalent of a substance is the **thickness of a lead layer that has the same weakening effect** as the observed material in the actual thickness.

Example: 100 kV of X-ray radiation weakens a 12-cm-thick brick wall as much as it weakens 1 mm of lead. This brick wall thus has a lead equivalent of 1 mm.

Lead rubber is also frequently used to protect against radiation. This protective effect depends on the lead equivalent and radiation quality (useful or stray radiation, tube voltage, filtration). Lead rubber weakens X-ray radiation down to a few per cent.

Effect of ionizing radiation

Ionizing radiation has an effect on cells affected by radiation. The respective effect can vary greatly and may also be fatal in some individuals depending on the intensity and type of radiation.

The following parameters must be defined in advance to describe the effect of ionizing radiation.

Energy dose

The energy dose describes a **quantity of energy absorbed by an object** (e.g., tissue) being radiated. It is primarily dependent on the radiation intensity of the ionizing radiation and the absorbency of the tissue. The unit of the energy dose is the **gray** [Gy].

Ion dose

The ion dose is defined as a size that provides the strength of the radiation. It is described by the following formula:

Ion dose = released charge / mass of the radiated substance

The ion dose is written with the unit columb/kilogram [C/kg]. (See article: Physics for Medical Students – Ionizing Radiation and Radioactivity)

Equivalent dose

The equivalent dose states **how strong or intense the biological effect** of a specific dose of radiation is. The unit for the equivalent dose is the **sievert** [Sv].

Biological effect

Molecules are destroyed by ionizing radiation. However, the damage caused solely by the momentarily radiated, and thus destroyed, molecules is relatively low. The damage caused by the subsequent chemical reactions in the body is much greater.

The various forms of this are:

- **Short-term exposure:**
  From 0.2 to 1 Sv: This may result in so-called **radiation sickness**. The symptoms of this affliction are quite various and may cause anything from minor long-term damage to even death. The process depends on the dose of radiation.
  From 4 Sv onward: In 50 % of the cases, such a dose of radiation leads to death.
  From 7 Sv onward: A dosage this high is always fatal. Characteristic damage includes a weakened immune system, burns, changes in DNA or even mutations.
- **Intermediate equivalent doses:**
  Mid-term equivalent doses equate to approx. 0.1 Sv. This is the dose that a person of 76 years of age has received through cosmic/natural radiation.
- **Lower equivalent doses:**
  This includes cosmic and terrestrial radiation (natural radiation).

The most dangerous type of radiation is **alpha radiation**. Its typically very short range ensures that the risk of alpha rays being harmful is very low. This is coupled with the fact that alpha radiation can be screened by a simple sheet of paper. It is dangerous when an object emitting alpha rays comes into direct contact with tissue (by inhaling radioactive dust or swallowing such objects).

Review Questions

The answers can be found below the references.

1. The photons created in an X-ray tube with 100 kV of anode voltage differ from those in a tube with 50 kV of anode voltage by:

(1) Maximum energy
(2) Maximum speed
(3) Maximum frequency
(4) Maximum wavelength

A. 1 and 2 are correct
B. 1 and 3 are correct
C. 1, 3 and 4 are correct

D. 2, 3 and 4 are correct
E. All are correct

2. An X-ray tube is operated at 60 kV. At approximately which speed are the electrons emitted by the cathode traveling upon reaching the anode? (e = 1,6 × 10^{-19} As; m_e = 9,1 × 10^{-31} kg)

A. 7 x 106 m/s
B. 1,5 x 107 m/s
C. 4,5 x 107 m/s
D. 1,4 x 108 m/s
E. 3 x 108 m/s (speed of light)

3. A decrease in the anode voltage of an X-ray tube causes the spectrum to change in the same way as the reduction of the emission current, as both the decrease in the anode voltage of an X-ray tube and the reduction of the emission current decrease the radiation power of the tube.

A. Statement 1: correct, Statement 2: correct, Correlation: correct
B. Statement 1: correct, Statement 2: correct, Correlation: false
C. Statement 1: correct, Statement 2: false, Correlation: –
D. Statement 1: false, Statement 2: correct, Correlation: –
E. Statement 1: false, Statement 2: false, Correlation: –

References

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Correct answers: 1C, 2D, 3D

Notes