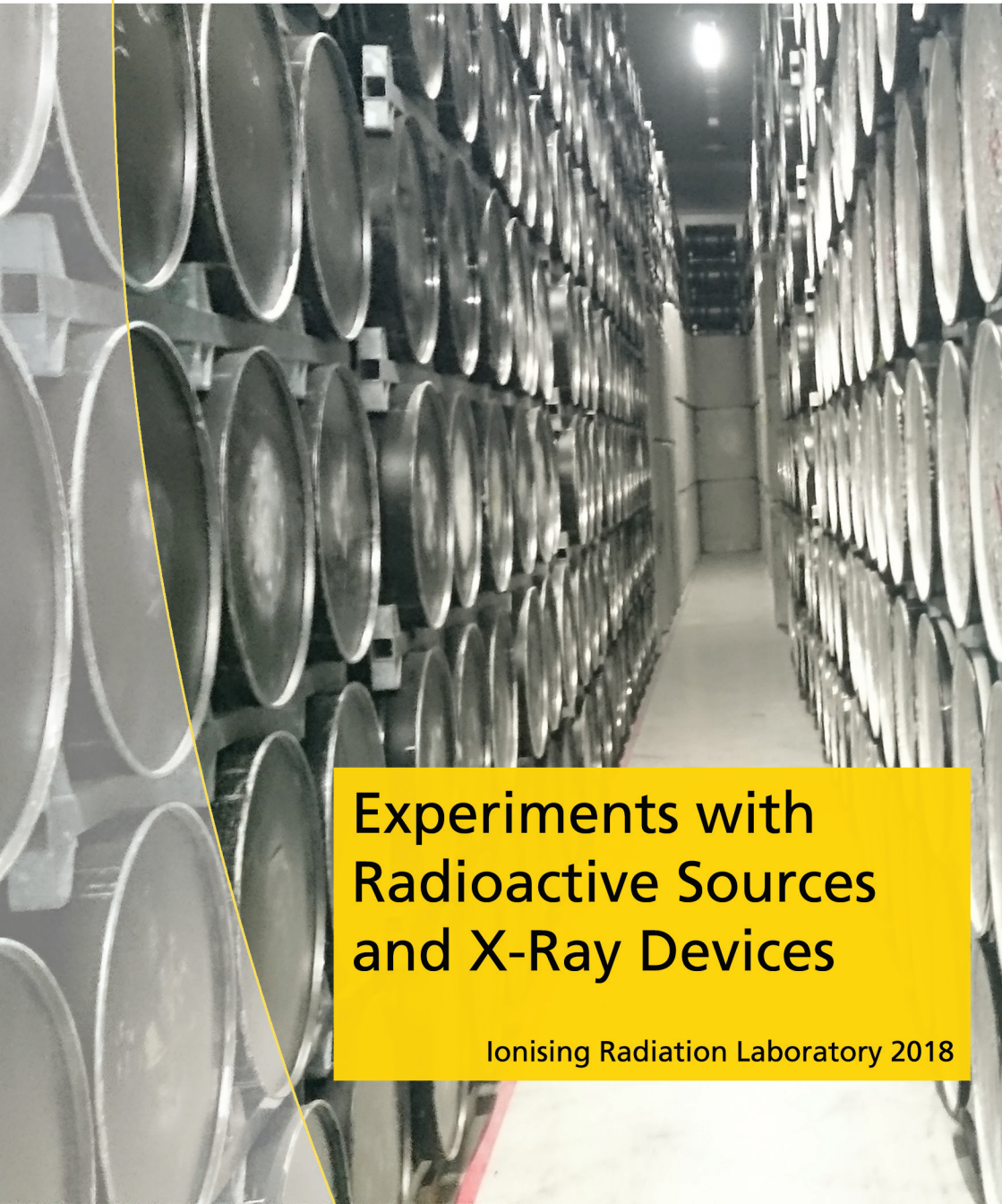
Utrecht University



Experiments with Radioactive Sources and X-Ray Devices

Ionising Radiation Laboratory 2018

Experiments with Radioactive Sources and X-Ray Devices

Ionising Radiation Laboratory | ISP

Experiments with Radioactive Sources and X-Ray Devices

Faculteit Bètawetenschappen, Universiteit Utrecht
www.freudenthalinstituut.nl

A Princetonplein 5, 3584 CC Utrecht
T 030 253 1178 | 1181
E science.isp@uu.nl
W www.stralenpracticum.nl

Introduction

We see a rainbow with our eyes, and we hear sound with our ears. But we do not have a sensory organ for detecting radioactivity or X-rays. Therefore, we do not notice that our body is continuously exposed to ionising radiation.

We receive radiation from the cosmos and from the Earth's soil. Our own body also contains radioactive substances. This ever present radiation is called the *background radiation*. The radiation dose we receive through this background radiation varies with the place on Earth. In the Netherlands this concerns an average equivalent dose of roughly 1.8 mSv/year.

In the physics lessons you have already learned about the properties and laws of radioactivity and X rays. By performing some experiments in the *Ionising Radiation Laboratory* you will extend that knowledge. The radiation sources used are quite weak and well shielded. As a result, the extra radiation dose of 0.2 μSv/hour you receive during a laboratory session is smaller than the variations in the background radiation.

The laboratory consists of some twenty different experiments. With this booklet you can prepare for performing a number of those experiments. For each experiment, some information is given about the theory, the aim, the set-up and some real-world applications.

On the page 'background information' on the ISP website you will find a summary of the theory about radioactivity and X-rays, an overview of the effects of ionising radiation on the human body and more information about real-world applications of ionising radiation.

In the laboratory each experiment is equipped with a worksheet with assignments about gathering and processing the measurement results. If these assignments are unclear to you, then ask the ISP staff member for help.

In general you are not allowed to eat and drink during a laboratory session. This also applies to the *Ionising Radiation Laboratory*. Most of the devices that you will work with during the laboratory session will be unfamiliar to you. Therefore, the buttons you have to operate have been marked *yellow*. As long as you do not touch the other buttons, the experiments can be carried out without any problem. Good luck.

Utrecht, November 2018
the lab teachers:
Lukman Mahmud Sofy, Rob van Rijn, Jan Beks and Ad Mooldijk

The ISP website offers additional information about the properties and effects of ionising radiation and about real-world applications such as carbon dating, neutron activation analysis, art historical research, medical imaging, production of medical isotopes and materials research with X-ray diffraction (in Dutch):
stralenpracticum.nl > students > background information

Contents

Experiments

You will need the sections ‘Table of Isotopes’ and ‘Single Logarithmic Graph Paper’ in some of the assignments on the worksheets. The ‘List of Concepts’ is useful for quickly finding the meaning of words unknown.

Availability

The three mobile laboratories are equipped with Experiments 1 to 21.
Experiments 1 and 19 are not available in Utrecht.

Classification

The experiments are classified in the following three groups:

Red: Half-life	2A – 2B – 10 – 20 – 21
Blue: Absorption	1 – 5 – 11 – 12 – 13 – 18 – 19 – 22
Green: Miscellaneous	3 – 4 – 6 – 7 – 8 – 9 – 14 – 15 – 16 – 17 – 23

Range of Alpha Particles in Air

Introduction

In air, α particles (helium nuclei) gradually lose their energy in interactions with nitrogen and oxygen molecules. In such an interaction the α particles transfer part of their energy by ionising the nitrogen or oxygen molecules. The energy required for ionisation averages 32 eV per electron. In an *ionisation chamber* the charge of electrons and ions created by these α particles is measurable as an electric current.

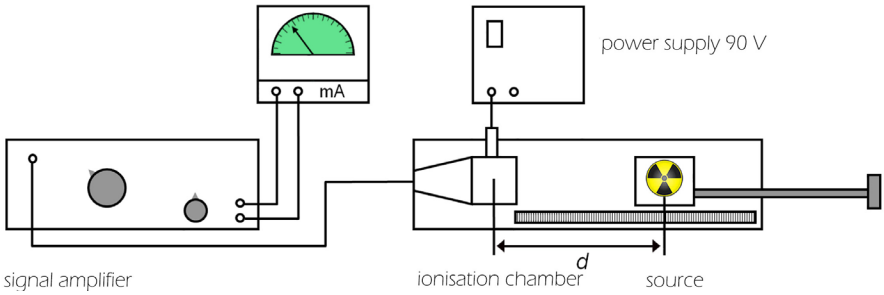
The α particle transfers its energy over a certain distance, after which it catches two free electrons and becomes a neutrally charged helium atom. This helium atom no longer possesses any ionising capacity. The distance required for an α particle to transfer all its energy is called its *range*.

Aim

To measure the range in air of α particles emitted by a source of radium-226.

Set-up

The set-up consists of a source of radium-226 and an ionisation chamber. The distance between the source and the ionisation chamber is adjustable. The current in the ionisation chamber can be read on an ammeter after amplification by a signal amplifier.



Applications

Most smoke alarms make use of a radioactive source that emits α particles. The range of these α particles declines in smoke-filled air, which is detected by the device. When this occurs, the alarm goes off.

When producing plastics such as synthetic yarn, the product becomes electrically charged. This impedes the production process. The charge can be removed by ionising the surrounding air using a source of α particles. The range of the α particles determines the location of the source in the production room.

The ISP website provides background information about the range of α particles in air (in Dutch): stralenpracticum.nl > students > background information > range of α particles in air

---

Radioactive Decay of Radon-220

Introduction

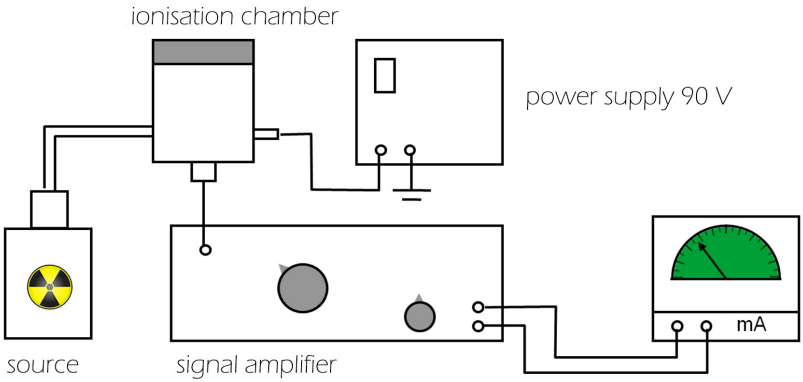
Some natural isotopes are unstable: they decay to become different isotopes by emitting ionising radiation. For example, radium-226 decays to the stable lead-206. It is impossible to predict when an instable nucleus decays, but when observing large numbers of instable nuclei of the same isotope a general pattern of decay emerges. During a certain time period half of the instable nuclei decay. This time period is called the *half-life* of an isotope. The value of the half-life depends on the isotope, and varies from fractions of a second to millions of years.

Aim

To measure the half-life of radon-220.

Set-up

The set-up consists of an ionisation chamber that is filled with radon gas from a small plastic bottle containing a source of thorium-232. The α particles emitted by the radon-220, which is itself a decay product of thorium-232, ionise the air in the ionisation chamber. The charge produced is displayed as a current on an ammeter (experiment 2A) or a plotter (experiment 2B) after amplification by a signal amplifier.



Applications

When estimating the age of a material through *carbon dating*, the activity of radioactive carbon-14 is measured. The half-life of this isotope is 5730 years. The measured activity of carbon-14 and its known half-life determine the approximate age of the material. This dating method is often used in archaeological research (see also Experiment 21).

Radioactive isotopes with a short half-life are used as a *tracer* in medical diagnoses of heart problems, brain tumours and thyroid diseases (see also Experiment 10).

Statistical Variation

Introduction

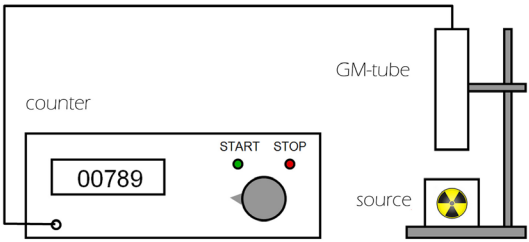
For a radioactive source with a long half-life, the number of unstable nuclei decaying per unit of time is almost constant. However, radioactivity is a statistical phenomenon. Predicting when a certain unstable nucleus will decay remains impossible, as every nucleus has a certain chance to decay. The number of decaying nuclei per unit of time is therefore not a true constant, but varies around a certain average number. Suppose this average number is valued at N. According to statistical theory, the size of the variations around the average number then is $\sqrt{N}$. The number of voltage pulses per unit of time, as measured with a Geiger-Müller tube, will therefore show a similar statistical character.

Aim

- To show that the number of disintegrations of unstable nuclei as measured in pulses per second is not constant, but varies around N.
- To check whether this variation around the average N of the measured number of pulses is approximately $\sqrt{N}$.

Set-up

The set-up consists of a Geiger-Müller tube, a pulse counter and a source of radium-226.



Applications

There are no practical applications for the statistical character of radioactivity. However, this experiment shows that the number of pulses needs to be large enough in order to reach a certain measurement accuracy. For instance, when measuring 100 pulses, the deviation will be $\sqrt{100} = 10$ pulses. This is a measuring inaccuracy of 10/100 = 0.10 or 10%. When measuring 10,000 pulses, the inaccuracy is reduced to 1%. So, the larger the number of pulses measured is, the better is the accuracy of the measurement.

Back Scattering of β Particles

Introduction

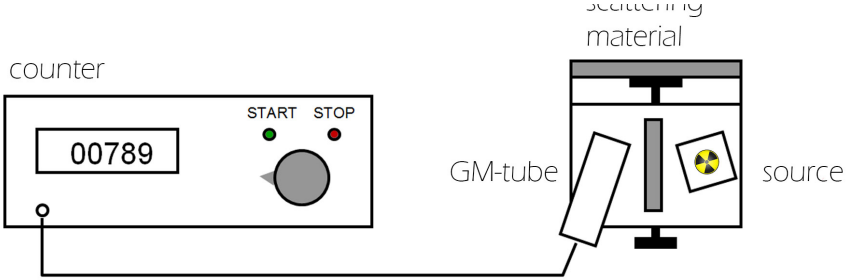
When β particles collide with matter, absorption may occur. Another possible result is the occurrence of *scattering* by elastic collisions of β particles with electrons in the material. Such a collision changes the speed and the direction of the β particles. With increasing atomic number Z of the material, the chance that a collision results in a scattering of the β particle increases too. When the β particle's direction of motion roughly reverses, the phenomenon is called *back scattering*.

Aim

To determine the relation between the number of back scattered β particles and the atomic number of the scattering material..

Set-up

The set-up consists of a Geiger-Müller tube, a pulse counter, an apparatus to position sheets of different scattering materials, and a source of strontium-90 that emits mostly β radiation.



Applications

One of the applications of back scattering of β particles is measuring the thickness of a surface layer on vinyl carpets. During the production process the back scattering is continuously measured. The number of back-scattered particles changes if the thickness of the surface layer changes. The production process is then automatically adjusted until the number of back-scattered particles returns to its original value.

Similarly, the thickness of a layer of asphalt on a road can be measured and controlled during road works

.

Absorption of β Particles in Aluminium and Perspex

Introduction

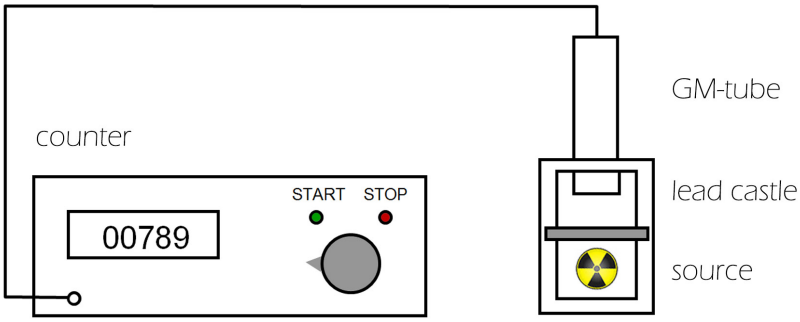
In matter β particles lose their energy in collisions with atoms of the material when they ionise these atoms. A radioactive source emits β particles with a range of energies. The larger their energy is, the longer is the path of the β particles in the material. But also the density of the material influences the length of this path. The maximum length of the path in the material is called the *range* of the β particles. When the thickness of a material is smaller than the range of the β particles, some of the particles will pass through the material.

Aim

- To determine the relation between mass per unit of area (the product of thickness and density) of the absorbing material and intensity of the transmitted β radiation.
- To measure the universal range and the range of β particles in aluminium and perspex.
- To measure the maximum energy of β particles, emitted by a source of strontium-90.

Set-up

The set-up consists of a Geiger-Müller tube mounted in a 'lead castle', a pulse counter, and a source of strontium-90. Sheets of aluminium and perspex can be inserted between the GM tube and the source in the lead castle.



Applications

The relation between the thickness of a material and the intensity of the transmitted β radiation is used in industry for filling bottles, and for measuring en controlling the thickness of paper and plastic foil during the production process.

In addition, the limited range of β particles in aluminium and perspex makes these light materials suited for shielding β sources in the context of radiation protection.

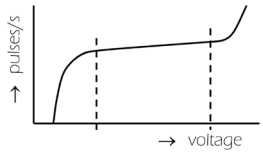
The ISP website provides background information about the universal range of β particles (in Dutch): stralenpracticum.nl > students > background information > universal range

Geiger-Müller tube

Introduction

The Geiger-Müller tube consists of a cylinder filled with a gas under low pressure. A metal rod is fixed on the cylinder's axis, insulated from the cylinder's wall. The rod and wall are connected to the positive and negative pole, respectively, of a high voltage power supply.

A radiation particle that enters the GM tube causes ionisation of gas atoms in the cylinder. The positive ions and free electrons then move towards the cylinder's wall and rod, respectively. During their motion the electrons acquire a speed large enough to ionise new gas atoms. This ionisation process repeats itself many times, so that an avalanche or snowball effect is observed. This causes a voltage pulse over the tube's output. Such a voltage pulse can be registered with a pulse counter.



The graph shows the counting rate of a GM tube as a function of the voltage over the tube. The GM tube functions properly if the voltage lies in the horizontal part of the graph. This voltage is called the *operating voltage*.

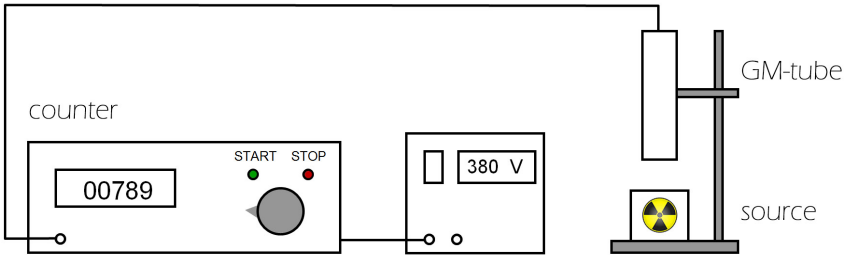
The GM tube only detects part of the incoming radiation. The *counting efficiency* of the GM tube is the number of detected particles divided by the number of incoming particles

Aim

To measure the operating voltage and the counting efficiency of a Geiger-Müller tube.

Set-up

The set-up consists of a Geiger-Müller tube, a pulse counter with a variable high voltage supply for the GM tube, a voltmeter, and a source of strontium-90.



Applications

The Geiger-Müller tube is often used for detection of radioactive contamination.

The ISP website provides background information about this radiation detector (in Dutch): stralenpracticum.nl > students > background information > Geiger-Müller tube

Energy of β particles

Introduction

Charged particles moving in a magnetic field experience a *Lorentz force*, that causes the particles to move in a curved path. When the particles' direction of motion is perpendicular to the direction of the magnetic field, the path of the particles will be circular. The Lorentz force F_L is providing the required centripetal force F_c. This allows us to determine the velocity v, and thus the energy of the particles, from the radius r of the circular path:

$$F_L = F_{mpz} \rightarrow B \cdot q \cdot v = \frac{m \cdot v^2}{r} \rightarrow v = \frac{B \cdot q \cdot r}{m}$$

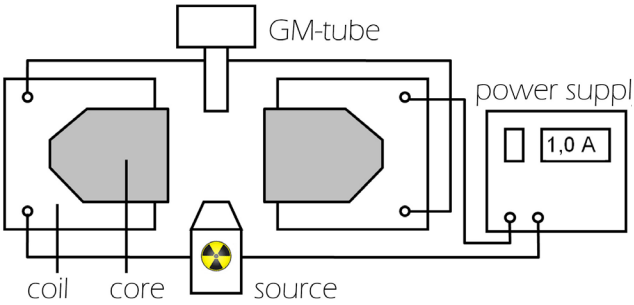
In this formula, B represents the magnitude of the magnetic field, q the charge and m the mass of the particles.

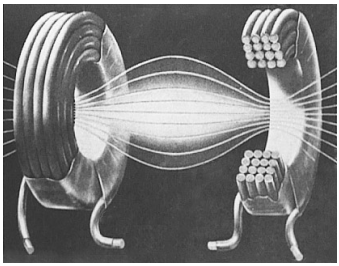
Aim

To measure the average speed and maximum energy of the β particles emitted by a source of strontium-90.

Set-up

The set-up consists of a U-shaped electromagnet. A current through the coils provides a homogeneous magnetic field between the two magnetic poles. The β particles from a source of strontium-90 pass through the magnetic field, are deviated and are detected by a GM tube.





Applications

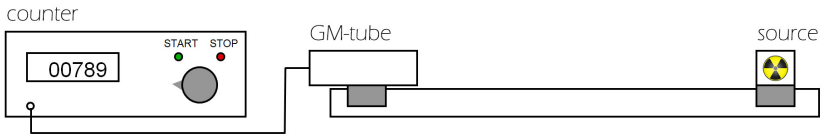
Deflecting the path of charged particles in a magnetic field is used in devices such as the cyclotron, the mass spectrograph and the 'magnetic bottle' (see the illustration on the left). The application as a magnetic bottle is used in nuclear fusion reactors to contain the particles in a confined space. In this way the deuterium and tritium nuclei in the plasma cannot escape the reactor.

Radiation Intensity and Distance

Introduction
When the distance between a source of radiation and a receiver increases, the radiation intensity at the location of the receiver decreases. This applies to sources of sound and light, and also to radioactive sources.

Aim
To determine the relation between radiation intensity and distance to a radioactive point source.

Set-up
The set-up consists of a Geiger-Müller tube, a pulse counter, and a source of strontium-90. The distance between the GM tube and the source is adjustable.



Applications
The radiation dose someone working with radioactive materials is exposed to, is reduced by limiting the time spent in close vicinity of the source and/or by increasing the distance to the source. Therefore, when working with radioactive materials, quite often mechanical handling tools will be used.

Wilson chamber

Introduction

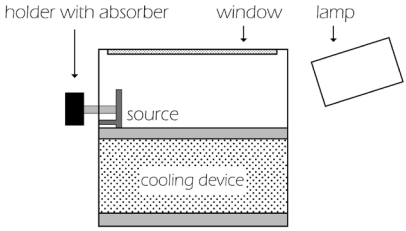
Our senses cannot detect ionising radiation. With an expansion chamber or a Wilson chamber you can observe visible traces of α and β particles. These particles ionise nitrogen and oxygen molecules in the air they pass through. These ions are condensation cores for the oversaturated water or alcohol vapour in the chamber. The path of the particles is then clearly visible as a condensation trail. In an expansion chamber such an oversaturated condition occurs by rapid extension of the air inside the chamber. This rapidly cools the air, causing oversaturation that allows for condensation around ionised molecules. The Wilson chamber maintains such an oversaturated condition by thermo-electric cooling of the bottom of the chamber.

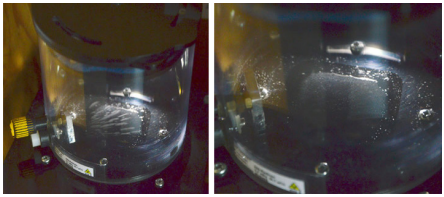
Aim

To observe the condensation trails caused by α and β particles emitted by a source of radium-226 and its decay products.

Set-up

The set-up consists of a continuous Wilson chamber with a source of radium-226. A lamp on the outside is used to illuminate the inside of the Wilson chamber.





Radium-226 emits α and β particles. In the photograph of the Wilson chamber on the left the trails of the α particles are clearly visible. In the photograph on the right the source is shielded with aluminium foil (thickness 0.2 mm). The trails of the β particles are so weak that they do not show on the photograph. The visible trail is caused by background radiation.

Applications

Photographs of particle trails in detectors such as an expansion chamber or a bubble chamber provide information about the structure of atomic nuclei and about the interaction between elementary particles in mutual collisions. The length of the condensation trail together with its curvature in a magnetic field allows inferences about the identity and characteristics of the particles.

The ISP website provides an enlarged photograph of the condensation trails in a Wilson chamber (in Dutch): stralenpracticum.nl > students > background information > Wilson chamber

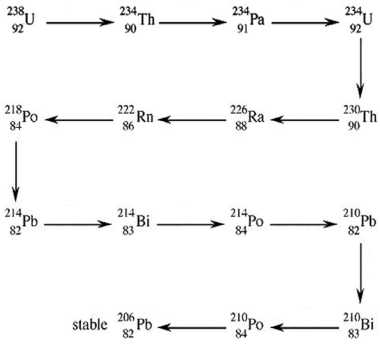
---

Recovery of Protactinium-234

Introduction

The decay product of some radioactive nuclides is itself also radioactive. This phenomenon is used in the protactinium generator with thorium-234.

100% of the unstable thorium nuclei decay directly to the protactinium-234m. The letter 'm' indicates that this is an isomeric state of the protactinium nucleus. That is a state in which the core has taken hold: the core has more energy than is the case in the normal ground state. Normally a nucleus loses this energy in a second decay step by emitting γ radiation (a γ-photon). However, 99.9% of the protactinium-234m formed directly decays to the unstable uranium-234. The complete expiry schedule can be seen below.



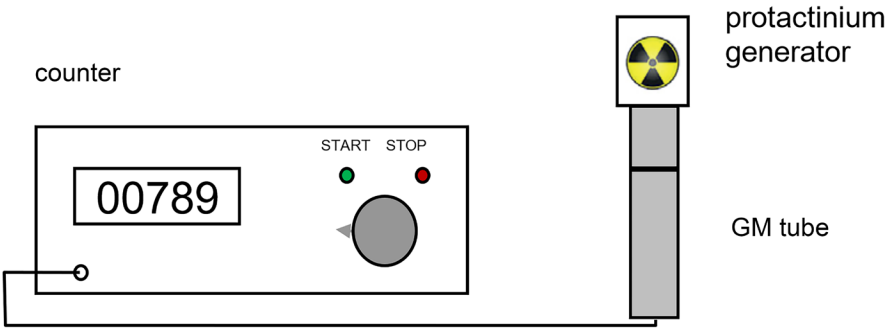
The half-life of thorium-234 is 24 days. That of uranium-238 is 4.5 · 109 years. Because the half-life of the 'mother' is much longer than that of the 'daughter', during the execution of the experiment the amount of thorium-234 is (almost) constant. The mentioned difference in half-times between the 'mother' (long) and the 'daughter' (short) then produces an equilibrium under normal circumstances. An equal number of protactinium-234m atoms are generated per second (from thorium-234) and decayed (to uranium-234). The generator then emits almost constant amounts of α-, β- and γ-radiation. In the generator there are two liquids with different densities: at the top an organic liquid (amyl acetate) and at the bottom a hydrochloric acid solution with uranium-238 and its decay products.

One of those decay products is the protactinium-234m. By shaking the generator, the protactinium ends up at the top of the generator, while the uranium and all other decay products remain at the bottom. This is due to a difference in solubility: protactinium dissolves better in amyl acetate (the upper liquid) compared to uranium and the other decay products. By removing the protactinium-234m the activity of the generator has been reduced. From the decay of thorium-234, new protactinium-234m is produced in the generator, which again emits radiation together with the other atoms that also form in the generator. The generator will recover and make atoms again until the old equilibrium is reached. By shaking, the protactinium can be removed and the recovery time of the generator can be measured.

Aim

Determine the recovery time of the generator from increasing activity during the recovery period.

Set-up
The set-up consists of a Geiger-Müller tube, a pulse counter, and a generator with uranium-238.



Applications
For scientific and medical research in plants, humans and other animals, radioactive nuclides with a short half-life are preferably used. Because of this short half-life, the activity of these nuclides is relatively high. The research can then be carried out with a relatively small amount of radioactive material. As a result, the radiation load of the organism remains low. However, these types of radioactive nuclides are difficult to obtain because of the rapid decay. The generator or 'radioactive cow' then offers a solution. This 'cow' can be milked shortly before carrying out the research at any time and then supplies the radioactive nuclide with the desired properties.

The uranium-238 in the generator in this experiment has a half-life of $4.5 \cdot 10^9$ years. This generator can therefore be used as a source of the short-lived protactinium-234m for a long time. In the same way, for example, the long-lived molybdenum-99 can be used as a source of the short-lived γ-radiator technetium-99m. This kind of radiation emitting nuclides with a short half-life are used as tracer (tracker) in research on, for example, heart defects (thallium-201), brain tumors (technetium-99m) and thyroid disorders (iodine-123).

The ISP website provides background information and a computer model for investigating the activity of the 'mother isotope' (the 'cow') and the 'daughter isotope' (the 'milk') in more detail (in Dutch): stralenpracticum.nl > students > background information > mother-daughter decay

---

Detection of Lead

Introduction

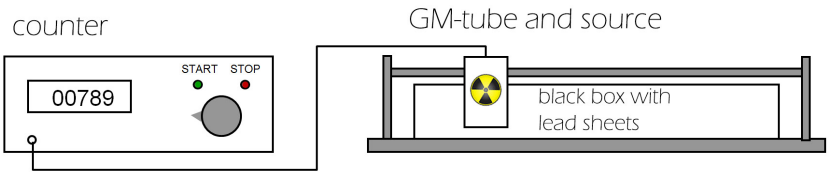
A beam of γ radiation will be partially absorbed by a sheet of lead. The larger the thickness of the sheet is, the larger is the absorption of the radiation and the lower is the intensity of the transmitted radiation. By comparing the intensities of the incident and transmitted radiation, the location and thickness of the absorbing material can be determined.

Aim

- To determine the location of several sheets of lead, hidden in a black box of plastic.
- To estimate and calculate the thickness of these sheets.

Set-up

The set-up consists of a rectangular black box of plastic, in which the sheets of lead are hidden. A Geiger-Müller tube and a source of cobalt-60 are mounted on opposite sides of a slide bar. The GM tube is connected to a pulse counter.



Applications

Absorption of γ radiation in materials is used in industry for measuring and controlling the thickness of steel plates during the manufacturing process, for measuring the liquid level in containers, for filling bottles, for detecting blockages in pipelines, for checking the quality of welds in constructions and so on. In all these applications a change in the material's thickness causes a detectable change in the intensity of the transmitted radiation.

Absorption of Gamma Radiation by Lead

Introduction

In the interaction between γ radiation and matter (such as lead), the intensity of the γ radiation gradually declines. In this, besides the ionisation of atoms, the *Compton effect* plays an important role.

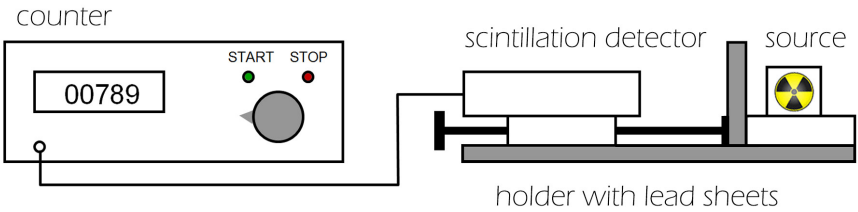
A measure for the absorption of γ radiation by matter is the thickness of the material at which the radiation intensity has declined to half its original value. This thickness of the material is called its *half-value thickness*.

Aim

- To determine the relation between thickness of the absorbing material and intensity of the transmitted γ radiation.
- To measure the half-value thickness of lead for the γ radiation emitted by a source of cobalt-60.

Set-up

The set-up consists of a scintillation detector, a pulse counter and a source of cobalt-60. Sheets of lead of different thickness can be inserted in the set-up between the detector and the source.



Applications

The absorption of γ radiation by lead makes this high-density material suitable for shielding γ sources in radiation protection. Unlike α and β sources, γ sources will never be shielded completely: with increasing thickness of the lead shielding, the intensity of the transmitted γ radiation continues to decrease, but never will become zero. Therefore, shielding of a γ source means lowering the radiation intensity to an acceptable level.

Other applications of γ radiation absorption by materials can be found in Experiment 11.

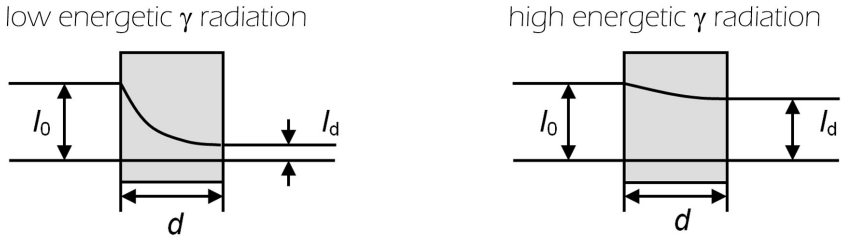
Qualitative Identification of Radioactive Sources

Introduction

The three kinds of ionising radiation (α, β and γ) have a different ionising power, and therefore a different penetrating power. The α particles, for example, have a large ionising power, but a very small penetrating power. For the γ photons it is exactly the opposite. The difference in penetrating power enables us to distinguish the different kinds of radiation with simple means.

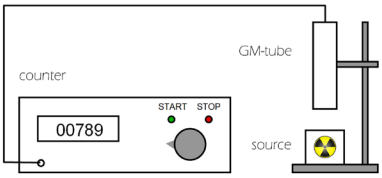
- The α particles are stopped by a sheet of paper or a few cm of air.
- The β particles are stopped by a sheet of aluminium of about 4 mm thickness.
- The γ photons are never stopped completely. For identifying this kind of radiation we use the *half-value thickness* of an absorbing material. The half-value thickness of lead for γ radiation is about 1 cm. This means: a lead sheet of 1 cm thickness absorbs about half of the incident γ radiation.

The absorption of γ radiation is not only determined by the kind of absorbing material and its thickness, but also by the energy of the γ radiation. The diagram below shows that the absorption of low-energetic (or: soft) γ radiation is larger than the absorption of high-energetic (or: hard) γ radiation



Aim

To identify the kinds of radiation emitted by unknown radioactive sources.



Set-up

The set-up consists of a Geiger-Müller tube, a pulse counter, some absorbers (sheets of paper, 4 mm aluminium and 4 mm lead) and three sources with unknown radioactive materials.

Applications

In order to take appropriate shielding measures in radiation protection, it is necessary to determine the properties of an unknown radioactive source. A first step then is a qualitative identification of the emitted radiation.

X-Ray Device

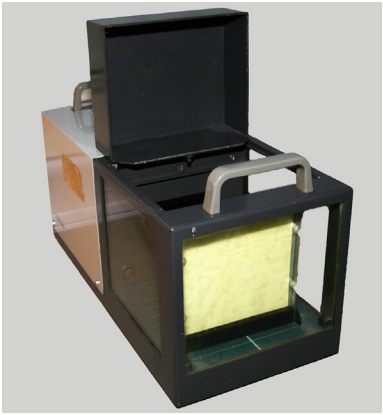
Introduction

X-rays are part of the electromagnetic spectrum. The X-ray spectrum lies between the areas of ultraviolet radiation and γ radiation. The X-ray wavelengths vary from 0.001 nm to 10 nm.

X-rays are generated in a high-vacuum tube in which electrons are accelerated by a voltage from the cathode across the tube towards the anode. When colliding with the atoms of the anode material, 99.5% of the kinetic energy of the electrons is converted into heat and 0.5% into X-rays. The maximum value of the acceleration voltage of the X-ray tube used in this experiment is 60 kV, so the minimum wavelength of the emitted X-ray photons is 0.021 nm.

Aim

To observe some properties of X-rays.



Set-up

The X-ray tube is contained in a case with a chamber of lead glass at the front. This glass absorbs almost all of the X-rays emitted by the tube. Moreover, the X-ray device will be switched off when this chamber is opened.

Objects can be placed inside the chamber. The absorption of X-rays by these objects can be observed by looking at the colour intensity on the fluorescent screen.

Applications

The X-ray device in hospitals is used for the diagnosis of bone fractures. Usually this involves creating two-dimensional images. In *X-ray computed tomography* (see Experiment 23), a three-dimensional image is created: a CT scan. This enables visualising body sections from any direction.

In scientific, medical and industrial research, X-ray diffraction (see Experiment 16) is used to determine the structure of complex molecules (such as protein and DNA molecules), the crystal structure of materials and so on. In industry, X-rays are, for example, used to check the quality of pipelines for the transport of natural gas.

The ISP website provides an applet simulating an X-ray photograph of a hand (in Dutch): stralenpracticum.nl > students > background information > X-ray photograph

Ionisation of Air by X-Rays

Introduction

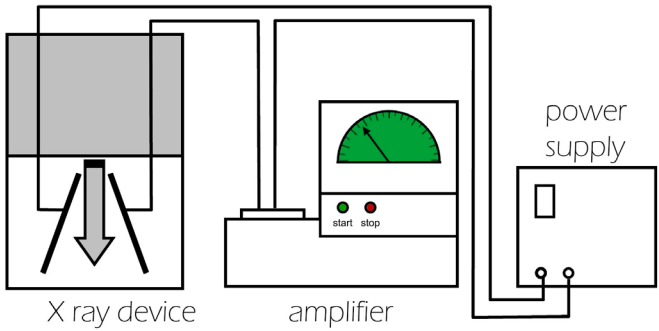
When a voltage is applied across two metal plates placed in air, no current is running because the air between the plates is not conductive. This changes when the air is ionised by X-rays. The formed ions can, of course, recombine with the free electrons to neutral atoms. But if the voltage across the plates is sufficiently high, the formed ions and free electrons move towards the plates. In this case, an ionisation current occurs, like in an *ionisation chamber*. At a certain voltage all ions and free electrons reach the two plates. The ionisation current has then reached its maximum. The amount of ion charge is used as a measure of the intensity of the X-rays. This is called the *exposure*. The unit of exposure is *roentgen* (R). Expressed in SI units – with charge in coulomb (C) and mass in kilogram (kg) – the value of the unit roentgen can be given as: $1\ \mathrm{R} = 2{,}58 \cdot 10^{-4}\ \mathrm{C/kg}$. The exposure per unit of time is called the *exposure rate*.

Aim

- To determine the relation between ionisation current and voltage across two capacitor plates when X rays pass between the plates.
- To measure the exposure rate of the X-ray tube

Set-up

The X-ray tube is contained in a case with a chamber of lead glass at the front. This glass absorbs almost all of the X-rays emitted by the tube.



Inside the chamber two capacitor plates are connected to a variable power supply. The X rays ionise the air between the plates. The resulting ionisation current is amplified and measured by an ammeter.

Applications

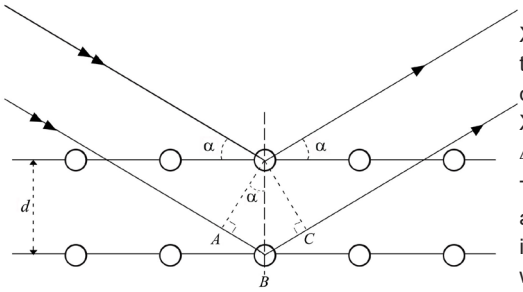
Measuring the rate of exposure in different places surrounding an X-ray device is a way to determine the quality of its shielding in radiation protection.

Applications of X-rays can be found in Experiment 14.

Bragg reflection

Introduction

The atoms in a crystal are arranged regularly. Their distance has a magnitude of about 10^{-10} m. This is comparable to the wavelength of X-rays. By using *X-ray diffraction*, the distance between the lattice planes in the crystal can be measured.



The figure on the left shows a beam of X-rays colliding with a crystal (of which only two lattice planes have been drawn). The difference in path length Δs of the two X-rays drawn is given by:

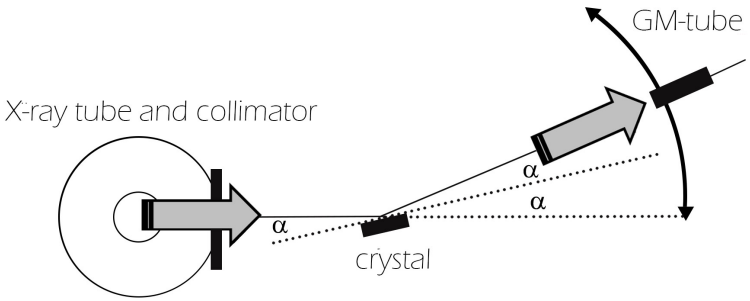
$\Delta s = AB + BC = 2 \cdot d \cdot \sin \alpha$.

The two reflected X-rays will be 'in phase' and thus maximally reinforce each other if this difference in path length equals a whole number of wavelengths n·λ. So, when: $n \cdot \lambda = 2 \cdot d \cdot \sin \alpha$.

In this formula λ is the wavelength of the X-rays and n is the order of the reflection (1, 2, 3 and so on). By measuring the angle α in which maximum reinforcement occurs, the distance d between the lattice planes of the crystal can be calculated.

Aim

To measure the distance between the lattice planes in a crystal by using X-ray diffraction.



Set-up

The set-up consists of a rotatable crystal, placed between a fixed X-ray tube and a Geiger-Müller tube. The GM tube is connected to a rate meter.

Applications

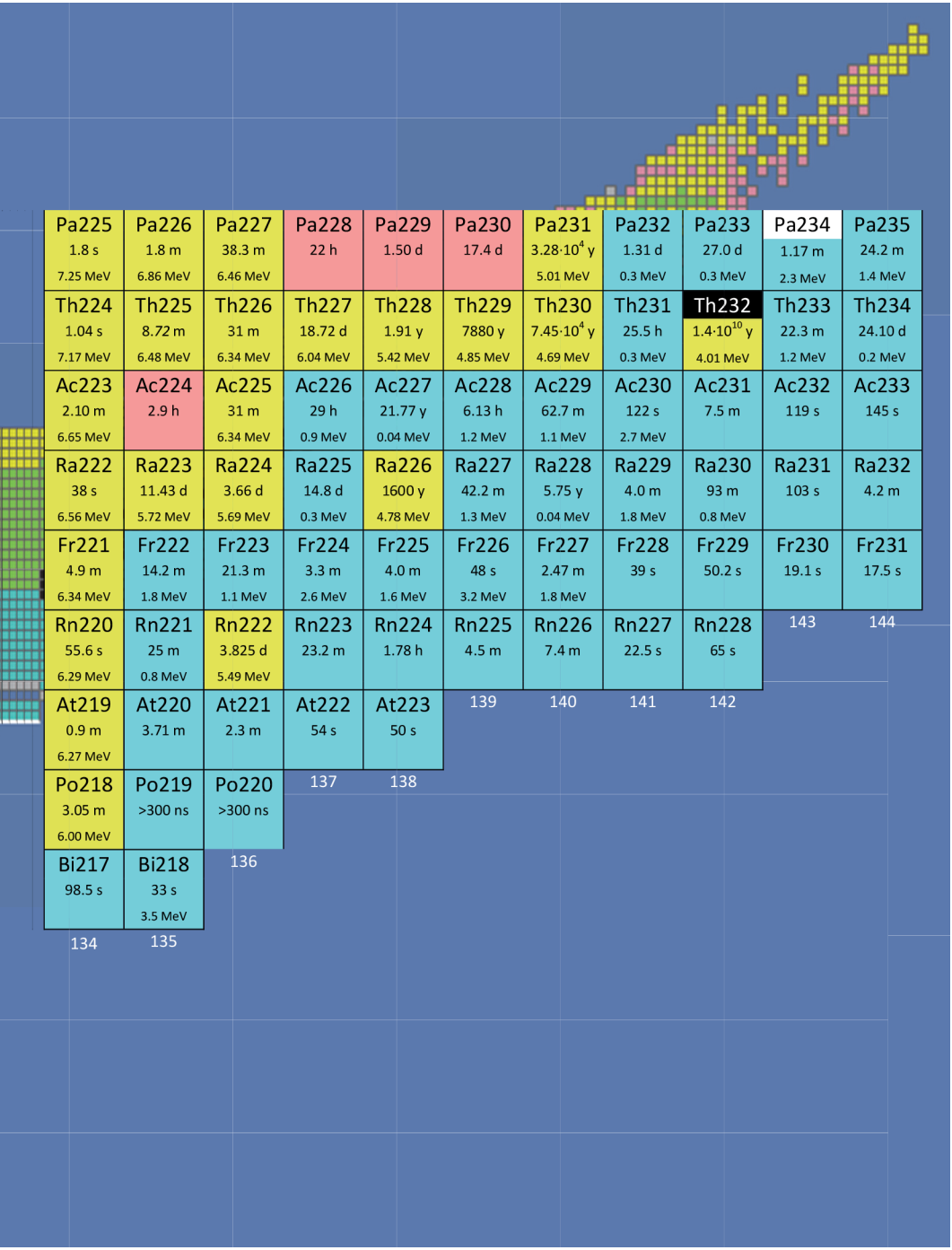
X-ray diffraction is used in materials research. From the diffraction pattern (showing the directions of maximum reinforcement), the structure of the crystal can be derived.

The ISP website provides an applet for investigating X-ray diffraction (in Dutch):
stralenpracticum.nl > students > background information > Bragg reflection

Table of Isotopes

number of protons	124	125	126	127	128	129	130	131	132	133
91	Pa215 14 ms 8.09 MeV	Pa216 105 ms 7.95 MeV	Pa217 1.1 ms 10.2 MeV	Pa218 113 µs 9.62 MeV	Pa219 53 ns 9.90 MeV	Pa220 0.78 µs 9.65 MeV	Pa221 5.9 µs 9.08 MeV	Pa222 4.3 ms 8.21 MeV	Pa223 6.5 ms 8.01 MeV	Pa224 0.95 s 7.56 MeV
90	Th214 0.10 s 7.68 MeV	Th215 1.2 s 7.39 MeV	Th216 26.0 ms 7.92 MeV	Th217 237 µs 9.26 MeV	Th218 0.1 µs 9.67 MeV	Th219 1.05 µs 9.34 MeV	Th220 9.7 µs 8.79 MeV	Th221 1.68 µs 8.15 MeV	Th222 2.24 µs 7.98 MeV	Th223 0.66 s 7.32 MeV
89	Ac213 0.8 s 7.36 MeV	Ac214 8.2 s 7.22 MeV	Ac215 0.17 s 7.60 MeV	Ac216 0.44 ms 9.03 MeV	Ac217 69 ns 9.65 MeV	Ac218 1.1 µs 9.21 MeV	Ac219 11.8 µs 8.66 MeV	Ac220 26 ms 7.85 MeV	Ac221 52 ms 7.65 MeV	Ac222 5.0 s 7.01 MeV
88	Ra212 13.0 s 6.90 MeV	Ra213 2.74 m 6.62 MeV	Ra214 2.46 d 7.14 MeV	Ra215 1.67 ms 8.70 MeV	Ra216 0.18 µs 9.35 MeV	Ra217 1.6 µs 8.99 MeV	Ra218 25.6 µs 0.04 MeV	Ra219 4.0 m 8.39 MeV	Ra220 23 ms 7.46 MeV	Ra221 28 s 6.61 MeV
87	Fr211 3.10 m 6.54 MeV	Fr212 20 m	Fr213 34.6 s 6.78 MeV	Fr214 5.0 ms 8.43 MeV	Fr215 0.09 µs 9.36 MeV	Fr216 0.70 µs 9.01 MeV	Fr217 16 µs 8.32 MeV	Fr218 1.0 ms 7.87 MeV	Fr219 21 ms 7.31 MeV	Fr220 27.4 s 6.68 MeV
86	Rn210 2.4 h 6.04 MeV	Rn211 14.6 h	Rn212 24 m 6.26 MeV	Rn213 19.5 ms 8.09 MeV	Rn214 0.27 µs 9.04 MeV	Rn215 2.3 µs 8.67 MeV	Rn216 0.3 ms 7.80 MeV	Rn217 0.54 ms 7.74 MeV	Rn218 35 ms 7.07 MeV	Rn219 3.96 s 6.82 MeV
85	At209 5.4 h	At210 8.3 h	At211 7.22 h	At212 314 ms 7.88 MeV	At213 0.11 µs 9.08 MeV	At214 0.56 µs 8.79 MeV	At215 0.1 ms 8.03 MeV	At216 0.3 ms 7.80 MeV	At217 32.3 ms 7.07 MeV	At218 ~2 s 6.69 MeV
84	Po208 2.898 y 5.12 MeV	Po209 102 y 4.88 MeV	Po210 138.38 d 5.30 MeV	Po211 0.516 s 7.45 MeV	Po212 0.3 µs 8.79 MeV	Po213 4.2 µs 8.38 MeV	Po214 164 µs 7.67 MeV	Po215 1.78 ms 7.39 MeV	Po216 0.15 s 6.78 MeV	Po217 1.53 s 6.54 MeV
83	Bi207 31.55 y	Bi208 $3.68 \cdot 10^5$ y	Bi209 $1.9 \cdot 10^{19}$ y 3.14 MeV	Bi210 5.013 d 1.2 MeV	Bi211 2.17 m 6.62 MeV	Bi212 60.60 m 2.3 MeV	Bi213 45.59 m 1.4 MeV	Bi214 19.9 m 1.5 MeV	Bi215 7.7 m	Bi216 2.17 m
82	Pb206 24.1 %	Pb207 22.1 %	Pb208 52.4 %	Pb209 3.253 h 0.6 MeV	Pb210 22.3 y 0.02 MeV	Pb211 36.1 m 1.4 MeV	Pb212 10.64 h 0.3 MeV	Pb213 10.2 m	Pb214 26.8 m 0.7 MeV	

number of neutrons


Pa225 1.8 s 7.25 MeV
Pa226 1.8 m 6.86 MeV
Pa227 38.3 m 6.46 MeV
Pa228 22 h
Pa229 1.50 d
Pa230 17.4 d
Pa231 3.28·10^4 y 5.01 MeV
Pa232 1.31 d 0.3 MeV
Pa233 27.0 d 0.3 MeV
Pa234 1.17 m 2.3 MeV
Pa235 24.2 m 1.4 MeV
Th224 1.04 s 7.17 MeV
Th225 8.72 m 6.48 MeV
Th226 31 m 6.34 MeV
Th227 18.72 d 6.04 MeV
Th228 1.91 y 5.42 MeV
Th229 7880 y 4.85 MeV
Th230 7.45·10^4 y 4.69 MeV
Th231 25.5 h 0.3 MeV
Th232 1.4·10^10 y 4.01 MeV
Th233 22.3 m 1.2 MeV
Th234 24.10 d 0.2 MeV
Ac223 2.10 m 6.65 MeV
Ac224 2.9 h
Ac225 31 m 6.34 MeV
Ac226 29 h 0.9 MeV
Ac227 21.77 y 0.04 MeV
Ac228 6.13 h 1.2 MeV
Ac229 62.7 m 1.1 MeV
Ac230 122 s 2.7 MeV
Ac231 7.5 m
Ac232 119 s
Ac233 145 s
Ra222 38 s 6.56 MeV
Ra223 11.43 d 5.72 MeV
Ra224 3.66 d 5.69 MeV
Ra225 14.8 d 0.3 MeV
Ra226 1600 y 4.78 MeV
Ra227 42.2 m 1.3 MeV
Ra228 5.75 y 0.04 MeV
Ra229 4.0 m 1.8 MeV
Ra230 93 m 0.8 MeV
Ra231 103 s
Ra232 4.2 m
Fr221 4.9 m 6.34 MeV
Fr222 14.2 m 1.8 MeV
Fr223 21.3 m 1.1 MeV
Fr224 3.3 m 2.6 MeV
Fr225 4.0 m 1.6 MeV
Fr226 48 s 3.2 MeV
Fr227 2.47 m 1.8 MeV
Fr228 39 s
Fr229 50.2 s
Fr230 19.1 s
Fr231 17.5 s
Rn220 55.6 s 6.29 MeV
Rn221 25 m 0.8 MeV
Rn222 3.825 d 5.49 MeV
Rn223 23.2 m
Rn224 1.78 h
Rn225 4.5 m
Rn226 7.4 m
Rn227 22.5 s
Rn228 65 s
143
144
At219 0.9 m 6.27 MeV
At220 3.71 m
At221 2.3 m
At222 54 s
At223 50 s
139
140
141
142
Po218 3.05 m 6.00 MeV
Po219 >300 ns
Po220 >300 ns
137
138
Bi217 98.5 s
Bi218 33 s 3.5 MeV
136
134
135

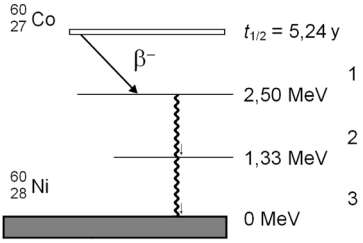
Gamma Spectrometry

Introduction

When an instable nucleus decays through emitting an α or β particle or is being bombarded with neutrons or other high-speed particles, the new nucleus often is in an excited state – a state with extra energy. Such a nucleus will then after a (mostly very short) period of time decay to its ground state – the state with minimal energy – by emitting a γ photon.

In this experiment we use the instable cobalt-60. This nuclide decays in three steps to nickel-60, as given by the decay scheme below.

- During the first step, cobalt-60 decays by emitting β radiation to nickel-60 in an excited state with an extra energy of 2.50 MeV.
- During the second step the excited nickel-60 decays to a lower excited state with an extra energy of 1.33 MeV by emitting γ radiation. This γ photon thus has an energy E_f of 2.50 –1.33 = 1.17 MeV.
- During the third step the still somewhat excited nickel-60 decays to its stable ground state (without any extra energy) by emitting γ radiation. The emitted γ photon thus has an energy E_f of 1.33 – 0 = 1.33 MeV.



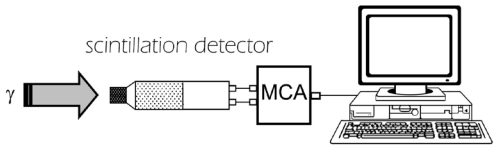
In summary, cobalt-60 emits γ radiation with two values of the photon energy: 1.33 MeV and 1.17 MeV. This we call the γ *spectrum* of cobalt-60.

Each nuclide has its own characteristic excited states of the nucleus and related values of the extra energy. Therefore, measuring the energy of the emitted γ photons – or: measuring the γ spectrum – allows us to identify the corresponding nuclide. This method is called *gamma spectrometry*.

Aim

- To measure the γ spectrum of an unknown source with the help of the known γ spectrum of a calibration source with cobalt-60.
- To identify the unknown source from its γ spectrum

Set-up



The set-up consists of a scintillation detector connected to a computer by means of a multichannel analyser (MCA), a calibration source of cobalt-60 and an unknown source.

Applications

Gamma spectrometry is used for identifying radioactive substances on the basis of their emitted γ spectrum in, for example, *neutron activation analysis*. In this technique, a material is bombarded with neutrons. As a result, radioactive nuclides are formed in the material. These nuclides can be identified by using gamma spectrometry. This allows scientists to establish, for example, whether or not a material is polluted, or whether or not a painting is a forgery.

Gamma spectrogram

In a gamma spectrogram there is more to see than the energy of the γ photons emitted during the decay of the nucleus to a lower energy state. Below the spectrogram of cobalt-60 is given as an example. The spectrogram shows the intensity of the γ radiation as a function of the photon energy.

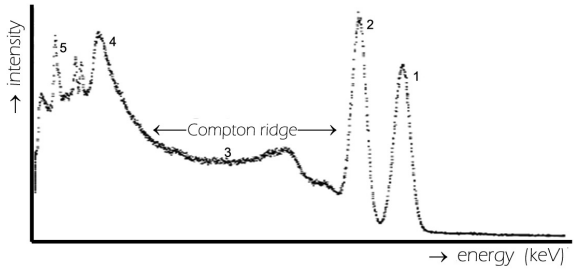


Photo peaks – The characteristic photo peaks of ^{60}Co are 1173 keV (peak 2) and 1332 keV (peak 1).

Compton ridge – The Compton ridge (3) originates when photons in collisions transfer part of their energy to free electrons in the scintillation crystal of the detector. The energy transferred can have any value between zero and a certain maximum. This explains the width of the Compton ridge.

Back scattering peak – The back scattering peak (4) originates from Compton scattering in the material surrounding the scintillation crystal. After these photons have transferred part of their energy, they re-enter the scintillation crystal through back scattering.

Lead peak – The lead peak (5) at 75 keV represents X-ray photons emitted by the lead shielding of the source. A photon emitted by ^{60}Co can free an electron from the K shell of a lead atom. This 'hole' in the K shell is filled by an electron from the L or M shell. The energy released in this process is emitted as an X-ray photon, which is detected by the scintillation crystal.

The ISP website provides background information about measuring γ radiation with a scintillation detector (in Dutch): stralenpracticum.nl > students > background information > gamma spectrometry

Elastic Modulus of Rubber

Introduction

For stretching a spring, a force is needed. The relation between force F and elongation $\Delta\ell$ is given by Hooke's law: $F = C \cdot \Delta\ell$. In this formula, C is the spring constant. Stretching a strip of rubber is comparable to stretching a spring. In the case of a strip of rubber, the relation between force F and elongation $\Delta\ell$ is given by

$$F = \frac{E \cdot A \cdot \Delta l}{l_0}$$

In this formula, E is the elastic modulus of rubber, A is the area of the strip's cross section and ℓ_0 is the strip's original length. In stretching the strip of rubber, both its width and its thickness change – and thus the area A of the strip's cross section. Determining the elastic modulus E of rubber therefore also requires measuring the width and the thickness of the strip of rubber. This thickness can be measured with the help of a radioactive source emitting β radiation.

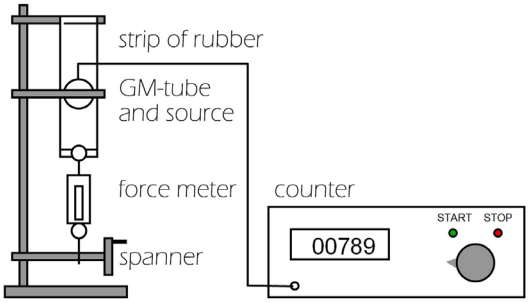
Aim

To measure the elastic modulus of rubber.

Set-up

The set-up consists of a strip of rubber, clamped to a force meter and a spanner (for stretching the rubber strip).

A source of strontium-90 and a Geiger-Müller tube are mounted on opposite sides of the rubber strip. The GM tube is connected to a pulse counter.



Applications

The relation between thickness of a material and intensity of the transmitted β radiation is used in industry, for example, for filling bottles, and for measuring and controlling the thickness of paper and plastic foil during the production process.

Range of Alpha Particles and Air Pressure

Introduction

An α particle causes ionisation in the material in which it moves. At each ionisation, the particle loses part of its kinetic energy. After having moved over a certain distance, the particle has transferred all its energy. This distance is called the *range* of the α particle. The value of this range depends on the density of the material. The range of α particles in tissue or water is some µm. In air, the range of these particles is much larger because of the much lower density of air as compared to tissue or water. The relation between range and density also indicates that the range of α particles in air will depend on the air pressure.

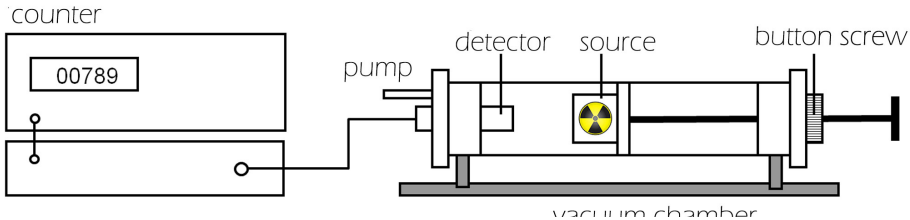
The range of α particles also depends on the energy they have when leaving the source. In this experiment we use a source of americium-241. This source emits α particles with the same energy (5,5 MeV), and these particles therefore should all have the same range. However, within the source the α particles are somewhat slowed down – one particle more than another. As a result, they leave the source with somewhat differing velocities. In this experiment we will look at the α particles having the highest velocity.

Aim

To determine the relation between range of α particles in air and air pressure.

Set-up

The set-up consists of a detector, a pulse counter, a vacuum chamber and a source of americium-241. The vacuum chamber can be closed with a button screw. The air pressure in the vacuum chamber can be adjusted with a hand-operated vacuum pump, and can be read on a pressure meter.



Applications

The relation between range of α particles and air pressure (or, more in general: the pressure of a gas) is used in industry, for example, for measuring and controlling the pressure in gas storage tanks.

Radioactive Decay of Protactinium-234

Introduction

Uranium-238 decays through a large number of steps to, eventually, lead-206. In this series protactinium-234 is one of the decay products. In this experiment we measure the half-life of this nuclide by using a protac¬tinium generator.

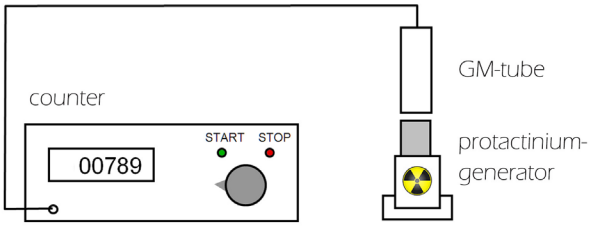
This generator contains two liquids of different densities: at the top an organic liquid (amyl acetate) and at the bottom a hydrochloric acid solution with uranium-238 and its decay products. One of those decay products is protac-tinium-234. By shaking the generator, the protactinium will concentrate at the top, while the uranium and all other decay products remain at the bottom of the generator. This is caused by a difference in solubility: protactinium dissolves better in amyl acetate (the liquid at the top of the generator) as compared to uranium and the other decay products. In this way, the protactinium can be isolated and its half-life can be measured.

Aim

To measure the half-life of protactinium-234.

Set-up

The set-up consists of a protactinium generator, a Geiger-Müller tube and a pulse counter.



Applications

Using the known half-life of radioactive nuclides, the age of objects can be determined. A prominent example is the method of *carbon dating*. This method is based on the decay of carbon-14 in objects containing organic material, such as canvas, paper and paint on old paintings (see also Experiment 21).

For dating rocks, the *uranium-lead method* is used. This method is based on the decay of uranium-238 to lead-206

.

Age of Radioactive Sources

Introduction

The age of a radioactive source with a known half-life can be determined if the original activity of the source is known. After measuring the actual activity of the source, the number of half-lives that have passed since then – and thus the age of the source – can be calculated.

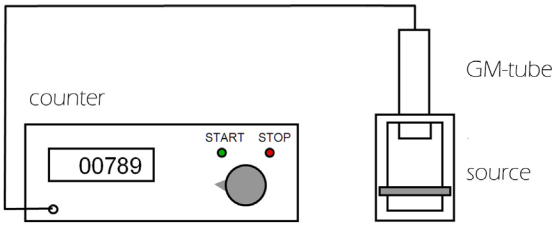
This experiment is a simulation of *carbon dating*. Materials such as paper and canvas are made from organic substances (of plants and animals). Such organic substances for a large part consist of carbon, most of it in the form of stable carbon-12 (^{12}C). However, a small, almost constant and known percentage of this carbon is the radioactive carbon-14 (^{14}C) that is taken up from the atmosphere by the organism during its life time. With the death of the organism, the uptake of ^{14}C stops. From that moment on, the percentage of ^{14}C in the organic material decreases through radioactive decay. From measuring the actual percentage of ^{14}C in organic material, its age can be calculated by also using the known original percentage of ^{14}C and its known half-life of 5730 years.

Aim

To measure the age of a number of radioactive sources.

Set-up

The set-up consists of a Geiger-Müller tube, a pulse counter and a number of cobalt-60 sources. The GM tube is mounted in a holder. The sources have the form of a sheet that can be inserted in the holder.



Applications

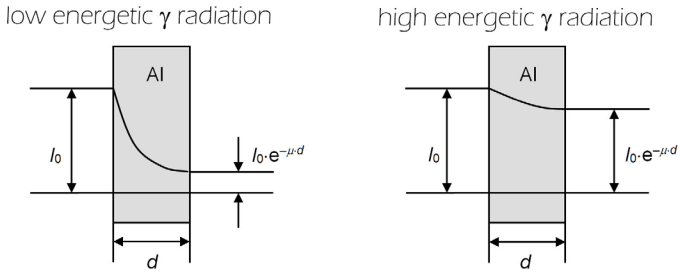
The age of objects can be determined with the help of the known half-life of radioactive nuclides. Art historians and archaeologists, for example, want to know whether or not certain objects do indeed date from a specific cultural period. Also in science, knowledge about the age of objects is important. From the age of layers of ice in polar regions, for example, conclusions can be drawn about climate changes in the far-away past. Such knowledge is useful for validating the computer models used to predict future climate change.

Coefficients of Absorption of Aluminium for Gamma Radiation

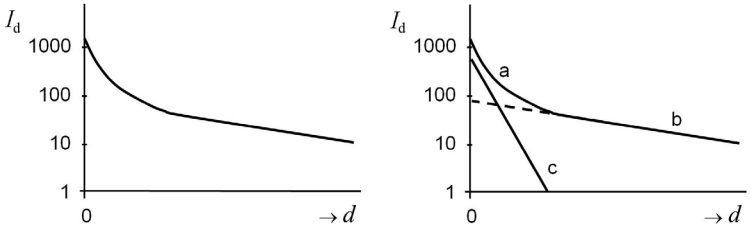
Introduction

In the interaction between γ radiation and matter (such as aluminium), the intensity of the γ radiation gradually declines. In this, besides ionisation of atoms, the *Compton effect* plays an important role.

The absorption of γ radiation not only depends on the kind of absorbing material and its thickness, but also on the energy of the γ radiation. The diagram below shows that the absorption of low-energetic (or: soft) γ radiation is larger than the absorption of high-energetic (or: hard) γ radiation.

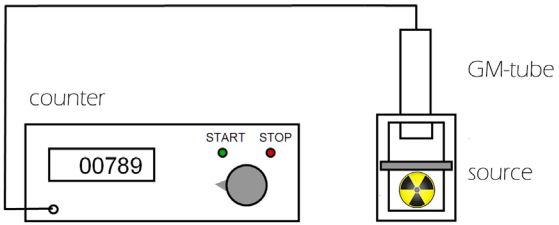


The source of americium-241 used in this experiment not only emits α radiation, but also γ radiation with photon energies of 27 keV and 60 keV. The intensity I_d of the transmitted γ radiation as a function of thickness d is shown in the diagram below (left) on a logarithmic vertical axis. The 27 keV γ radiation is almost fully absorbed at a relatively small thickness. The last part of the curve – the straight line (b) – thus represents the absorption of the 60 keV γ radiation only. This straight line (b) can be extrapolated to a thickness zero. The contribution of the 27 keV γ radiation (c) can now be found by subtracting the extrapolated line (b) from the original curve (a). From the two straight lines (b and c) the half-value thickness $d_{1/2}$ – and from that the coefficient of absorption μ – for the high-energetic and low-energetic γ radiation can be determined.



Aim
To measure the coefficients of absorption of aluminium for high-energetic and low-energetic γ radiation.

Set-up
The set-up consists of a Geiger-Müller tube, a pulse counter, a source of americium-241 and a number of aluminium sheets of different thickness.



Applications
The applications of the absorption of γ radiation by materials can be found in Experiment 11.

X-Ray Computed Tomography

Introduction

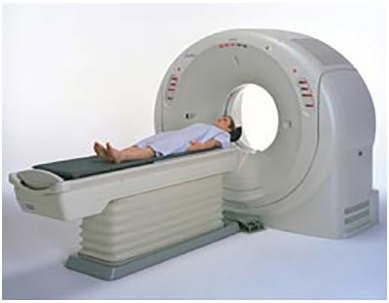
X-ray computed tomography (or, for short: CT) produces images of the human body's interior. The difference with making a normal X-ray image is that the patient is lying down horizontally while the X-ray tube and the detector rotate around the patient's body and take recordings from a large number of angles. These recordings are processed by a computer to show any desired cross section of the different tissues and organs in the body.

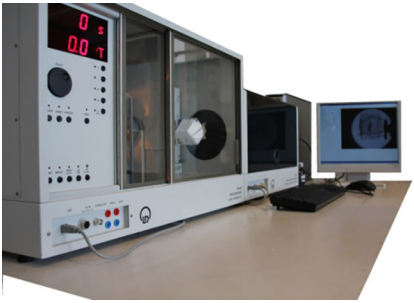
Aim

To observe some properties of X-ray computed tomography.

Set-up

The X-ray tube is contained in a case with a front of lead glass. This glass absorbs almost all of the X rays emitted by the tube. The X-ray device will be switched off when the front is opened. The case contains a holder for inserting objects. This holder can rotate over 360^{o} in adjustable steps. The computer screen shows the tomogram of an object in 3D (when wearing special 3D glasses) or in 2D. In both cases, also any desired cross section of the object can be selected for viewing on the screen.



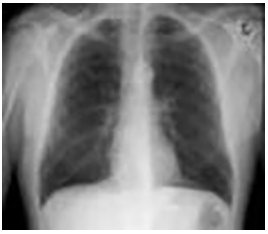


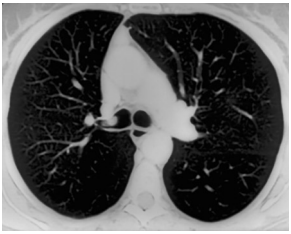
Left: X-ray CT scanner. *Right*: the set-up in which – contrary to the CT scanner in the hospital – the object to be investigated rotates. Rotating of the object instead of rotating the X-ray tube and detector has no effect on the images produced.

Applications

X-ray CT is used in the hospital for diagnostic purposes. On a 'normal' X-ray photograph the different structures in the body are overlapping each other, and are therefore difficult to distinguish. One of the problems is the lack of information about the exact location of, for example, a tumour. After a CT scan, the computer can produce an image of a cross section of the body in which the location of the tumour is clearly visible.

Moreover, X-ray CT also clearly distinguishes the different tissues in the body: lungs, bones, soft tissues and blood vessels.





Left: normal X-ray photograph of the lungs, on which the structures at different depths in the body are overlapping each other.
Right: computed cross section of the lungs after a CT scan.

Computed tomography is also applied in echography, magnetic resonance imaging (MRI) and medical imaging with radioactive tracers.

The ISP website provides background information about the way in which the computer calculates the image of an object from the recordings made at a number of different angles (in Dutch):
stralenpracticum.nl > students > background information > X-ray computed tomography

---

Single Logarithmic Graph Paper

Linear Relation

In order to find the relation between two variable quantities, you plot your measurement results in a graph and you draw a flowing curve that best fits the measurement points. The latter is relatively easy if the curve is a straight line, such as in Figure 1. In this case, the quantities *x* and *y* are proportional: $y = a \cdot x$. You can now use the graph for *interpolating* and for determining the value of the proportionality constant a in the formula $y = a \cdot x$ as accurately as possible.

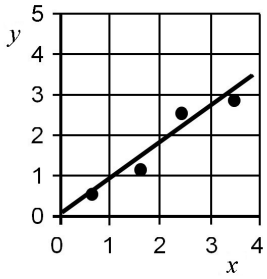


Figure 1 – Function $y = a \cdot x$

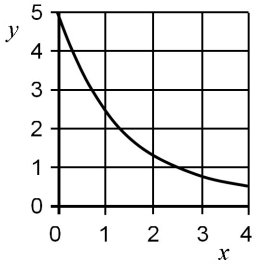


Figure 2 – Function $y = 5 \cdot a^x$ with $a = 0{,}5$

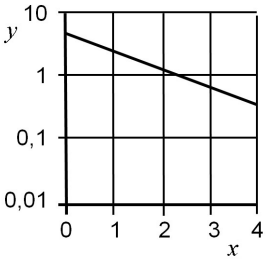


Figure 3 – Function $y = 5 \cdot a^x$ on single logarithmic graph paper

Exponential Relation

If the relation between the quantities *x* and *y* is of the form $y = a^x$ (such as in Figure 2), drawing a flowing curve that best fits the measurement points is somewhat more difficult. When dealing with radioactivity such an *exponential relation* between the quantities *x* en *y* applies to radioactive decay and to absorption of radiation by materials.

Radioactive Decay – The exponential relation $y = a^x$ can be recognised in the formula for the activity A_t of a radioactive source as a function of time *t*:

In this formula, the activity A_t compares to the quantity *y*, the time *t* compares to the quantity *x*, and the value of a is 0.5.

Radiation Absorption – A comparable exponential relation applies to the intensity I_d of the transmitted γ radiation as a function of the absorber's thickness *d*:

$$I_d = I_0 \cdot \left(\tfrac{1}{2}\right)^{d / d_{1/2}}$$

In this formula, the intensity I_d compares to the quantity *y*, the thickness *d* compares to the quantity *x*, and the value of a is (again) 0.5.

In both cases the graph will take the shape of a straight line when using *single logarithmic* graph paper.

Single Logarithmic Graph Paper

If the relation between the quantities x and y is of the form $y = a^x$ (see Figure 2), the mathematical theory of logarithms states: log y = log (ax) = x·(log a). In this, (log a) is a number: log a = log (0.5) = –0.30 in the case of radioactive decay or radiation absorption. So, then you can also say that the relation between log y and x is proportional: log y = –0.30·x. This means: a graph with log y (instead of y) plotted on the vertical axis and x plotted on the horizontal axis will give a straight line.

For making such a graph you use *single logarithmic* graph paper: graph paper with a logarithmic y-axis. The graph of Figure 2 will then look like the one in Figure 3: a declining straight line (that best fits the measurement points). By interpolating from such a graph, the half-life $t_{1/2}$ or the half-value thickness $d_{1/2}$ can accurately be determined.

An example is given in Figure 5, in which the measurements from Figure 4 are plotted on normal and single logarithmic graph paper. The measurements in Figure 4 show the radioactive decay of radon-220 (see Experiment 2A). De half-life of this nuclide can be determined more accurately from the graph on the right.

current I (mA)	6	5	4	3	2	1
time t (s)	0	12	25	55	81	140

Figure 4 – Measurements in Experiment 2A about the radioactive decay of radon-220.

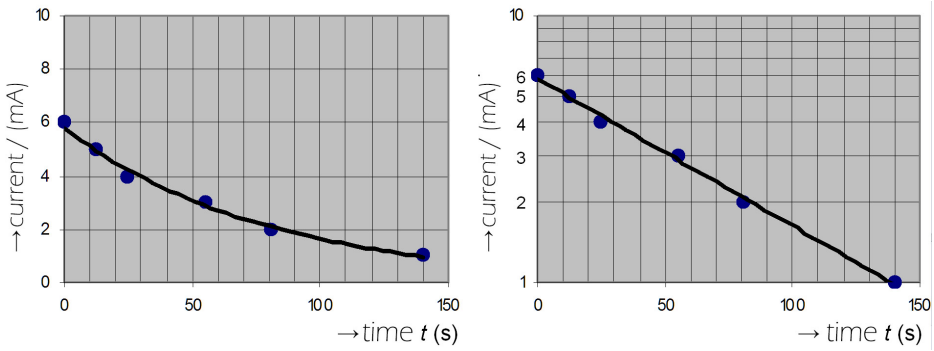


Figure 5 – Measurements from Figure 4, plotted on normal (left) and single logarithmic (right) graph paper.

List of Concepts

Absorber	Material that absorbs radiation
Absorption	Process in which radiation energy is transferred to matter
Activity (*A*)	Number of disintegrations per second in a radioactive source, expressed in the unit becquerel (Bq)
Alpha particle (α)	Positively charged helium nucleus, consisting of two protons and two neutrons
Alpha radiation (α)	Beam of α particles
Annihilation	Process in which a positron and an electron are converted into two photons
Atomic mass number (*A*)	Number of protons and neutrons in the atomic nucleus
Atomic number (*Z*)	Number of protons in the atomic nucleus
Background radiation	Radiation emitted by radioactive substances in nature, inside as well as outside the human body – also called 'natural radioactivity'
Back scattering	Interaction of particles with matter, in which the particles' direction of motion is more or less converted (reflection)
Becquerel (Bq)	SI unit of activity: 1 Bq = 1 disinte¬gration per secon¬d
Beta– particle (β–)	Negatively charged particle with a mass of 1/1837 of the mass of a proton: an electron
Beta+ particle (β+)	Positively charged particle with a mass of 1/1837 of the mass of a proton: a positron
Beta radiation (β)	Beam of β particles
Bragg reflection	Interference of X rays on the lattice planes of a crystal
Braking radiation	X rays emitted by decelerating electrons in the electric field of an atomic nucleus. Originally called Bremsstrahlung (German for 'braking radiation')
Collimator	Diaphragm for a beam of particles or radiation
Compton effect	Elastic interaction between a γ photon and an electron: the γ photon transfers part of its energy to the electron – one of the ways in which γ radiation loses its energy in matter
Cosmic radiation	High-energetic radiation from the cosmos
Curie (Ci)	Outdated unit of activity: 1 Ci = 3.7·1010 Bq. An activity of 1 Ci is the activity of 1 g radium

Decay series	Decay of a radioactive nuclide into subsequent radioactive nuclides
Detector	Material or instrument that is sensitive to radiation
Dose (*D*)	Absorbed radiation energy per kg of matter, expressed in the unit gray (Gy)
Dose meter	Instrument that registers the received radiation dose
Dose rate	Dose per unit of time
Electromagnetic radiation	Combined change of an electric and a magnetic field, propagating with the speed of light – for example, radio waves, light, X rays and γ radiation
Elementary particle	Particle that constitutes matter, such as the neutron, proton, electron, neutrino en muon
Equivalent dose (*H*)	Dose multiplied by a weighing factor depending on the kind of radiation (weighing factor 1 for X, β and γ radiation), weighing factor 20 for α radiation), expressed in the unit sievert (Sv)
Exposure	Charge per kg of air caused by ionisation through X rays, expressed in the unit roentgen (R)
Exposure rate	Exposure per unit of time
Film badge	Dose meter containing a photographic film. The dose received is determined from the degree of blackness of the film.
Fluorescence	Process in which a specific substances convert absorbed energy (of, for example, X rays) into light
Gamma photon (γ)	Energy quantum $E_f = h \cdot f$ in high-energetic electromagnetic radiation
Gamma radiation (γ)	Beam of γ photons
Geiger Müller tube	Detector for ionising radiation (especially sensitive to α and β particles): ionisation of gas atoms in the tube produces a voltage pulse
Gray (Gy)	SI unit of dose: 1 Gy = 1 J/kg
Half-life ($t_{1/2}$)	Time in which half of a radioactive substance decays
Half-value thickness ($d_{1/2}$)	Thickness of a material by which half of the incident X rays or γ radiation has been absorbed
Inverse square law	Decrease of the radiation intensity I with the square of the distance r to the (point) source: $I = c/r^2$
Ionisation	Process in which ions are formed

Ionisation chamber	Detector for ionising radiation: ionisation of gas atoms produces an electric current
Ionising radiation	Radiation that ionises atoms or molecules, such as X rays and α, β and γ radiation
Isomers	Nuclides with the same number of protons and neutrons, but with a different energy state of the atomic nucleus (ground state and excited states)
Isotopes	Nuclides with the same number of protons, but with a different number of neutrons (the atomic number is the same, the atomic mass number differs)
Multichannel analyser (MCA)	Electronic circuit that counts the voltage pulses of a scintillation detector and sorts these pulses according to pulse height
Neutrino	Uncharged and 'massless' elementary particle – very difficult to detect because of the extremely weak interaction with matter
Nuclide	General term for the atomic nucleus
Pair formation	Conversion of energy (for example, a γ photon) to matter under the influence of an electric or magnetic field, resulting in a particle and its antiparticle (for example, an electron and a positron, for which an energy of 1.02 MeV is needed)
Positron	See β+ particle
Pulse	Short-lived electric signal
Pulse counter	Instrument that counts voltage pulses given off by, for example, a Geiger-Müller tube
Rad	Outdated unit of dose: 1 rad = 0.01 J/kg
Radioactive decay	Spontaneous transformation of an unstable atomic nucleus into another nucleus or another energy state
Radioactive source	Amount of radioactive material, mostly in a closed container
Radioactivity	Process in which unstable atomic nuclei spontaneously emit an α or β particle or a γ photon
Range (R)	Maximum travelling distance of an α or β particle in matter
Rem	Outdated unit of equivalent dose (roentgen equivalent man)
Roentgen (R)	Unit of exposure: 1 R = $2.58 \cdot 10^{-4}$ C/kg

Scattering	Interaction of particles with matter, in which the particles' direction of motion arbitrarily changes
Sievert (Sv)	SI unit of equivalent dose: 1 Gy = 1 Sv for X, β and γ radiation; 1 Gy = 20 Sv for α radiation
Spectrometry	Analyses of radiation in terms of, for example, wavelength, energy and frequency
Tracer	Radioactive isotope used to investigate chemical or biological processes in, for example, the human body
X rays	Electromagnetic radiation with a wavelength of about 0.1 nm. This radiation originates as 'braking radiation' or radiation emitted when a 'hole' in an inner shell of an atom is filled by an electron from a higher shell

Radiation Risk

The human body is continually exposed to ionising radiation from natural sources. This causes an average equivalent dose of about 1.8 mSv per year. However, in the Netherlands this dose varies with a factor three, depending on the living environment. In addition to that, an average equivalent dose of 0.6 mSv per year is caused by artificial sources used for medical diagnostic purposes.

A radiation dose can do harm to the body, such as causing leukaemia and tumour growth in the long run. Therefore, the additional radiation exposure has to be kept as low as possible, among others by weighing the pros and cons of the use of radiation. So, in the case of a bone fracture an X-ray photograph will be made to see whether or not the bone fragments have been positioned in the right way. The advantage of a well-healed bone fracture counterbalances the disadvantage of the extra radiation dose.

Research has shown that an increase of the equivalent dose causes an increase in harm done to the body. The table below gives some risk numbers: the number of deaths from different kinds of cancer per year per million of people as a result of an extra equivalent dose of 10 mSv.

Tissue/organ	Number per year per million	Risk time (year)
Bone marrow	1,0	20
Lungs	0,5	40
Bone	0,1	40
Breast (women)	1,6	40
Thyroid gland	0,1	40
Total (men)	2,5	40
Total (women)	3,5	40

With the numbers in the table it can be calculated that an increase of the ‘natural’ radiation level from 2 to 4 mSv per year will cause the death of 1.5 persons per year from lung cancer in the Netherlands (having 15 million inhabitants). This number is small compared to the many thousands of cancer-related deaths per year.

Besides these long-term somatic effects, radiation can also have genetic effects. The assumption is that an equivalent dose of 1 mSv causes the birth of 2 children with genetic defects per million new-borns. Also this number is small compared to the 60 to 90 thousand per million new-borns with genetic defects resulting from other causes.

Very high radiation doses as caused by nuclear accidents or nuclear explosions affect the natural defence mechanism of the victims. They die of infectious diseases. The equivalent dose causing the death of 50% of the victims is estimated as 3.5 to 4 Sv. A dose of more than 10 Sv causes irreparable damage to the intestine system, a dose of more than 50 Sv does so to the central nerve system. In both cases, death will come within some days or hours. Such high doses are caused by nuclear explosions. In that case, however, the victims’ death results from damage caused by the high temperature and the shock wave.

Radiation Exposure

You are living in an environment in which you are exposed to ionising radiation. By filling in the table below, you will get an impression of the equivalent dose (in mSv/year) you receive. Note that this is nothing more than an impression, because in particular the radiation exposure through radon in the air (originating from the soil and building materials) strongly depends on the place where you live and work.

Contribution from	Radiation sources	mSv/year
Living environment	Cosmic radiation (at sea level)	0,25
	Soil	0,05
	Water and food	0,35
	Air	0,8
	Building materials	0,35
Free time	Airplane travel (at 10 km height): 5 µSv/hour	……
	Winter sports holiday (at 2 km height): 30 µSv/week	……
Health care	X ray chest cavity: 90 µSv	……
	X ray teeth: 0.1 mSv	……
	X ray breasts (mammography): 0.1 mSv	……
	X ray head and neck area: 0.2 mSv	……
	X ray hip: 0.8 mSv	……
	X ray bone fracture: 1 mSv	……
	CT scan head: 1.2 mSv	……
	CT scan body: 1.2 mSv	……
	Scintigram thyroid gland with ^{131}I: 4.3 mSv	……
	Scintigram skeleton with ^{99m}Tc: 6 mSv	……
	Scintigram heart muscle with ^{201}Tl: 17 mSv	……
Education	Ionising Radiation Laboratory (ISP): 0.2 µSv/hour	……
	Total equivalent dose in mSv/year	……

The ISP website provides background information about radiation sources and their contribution to radiation exposure, and about the effects of ionising radiation (in Dutch):
stralenpracticum.nl/ > students > background information > effects

Upper Secondary Laboratory and Quantum Lab

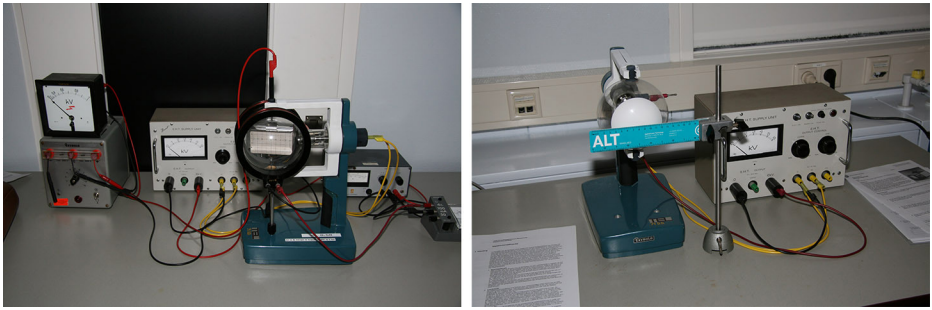
As a user of the Ionising Radiation Laboratory (ISP) you may also be interested in two other collections of experiments offered by Utrecht University: the Upper Secondary Laboratory (BBP) and the Quantum Lab. Structure-wise they are similar to the ISP, although BBP and Quantum Lab do not have a mobile lab.

BBP

The BBP consists of around fifteen experiments and exists for some time already. It has for instance a wind tunnel, a blood circulation model, solar cells, a tomography set-up and the possibility to measure the speed of light. Experiments about inertia and ultrasonic sound (acoustic lenses) are being developed. The Upper Secondary Laboratory is intended for whole classes visiting Utrecht University with their teacher, who will have the opportunity to encounter more complicated experiments. For more information, see www.fi.uu.nl/bbp.

Quantum lab

A series of experiments that relate to quantum physics is in the process of being developed. Some of the experiments are existing ones from BBP and ISP, such as for instance electron diffraction or the relation between charge and mass for the electron. New experiments are also being developed. The goal is to have a collection that presents a representative overview of both the many applications of quantum and its historical development.



Left: Set-up relation charge/mass for the electron. Right: Set up electron diffraction.

Both BBP and Quantum Lab involve experiments that, after good preparation, can be done in an hour or two. So a school can visit with two classes in one day.

Interested?

If you are interested in either of these series of experiments, please contact Science.Outreach.Phys@uu.nl.

Ionising Radiation Laboratory| ISP

Experiments with Radioactive Sources and X-Ray Devices

Faculteit Bètawetenschappen, Universiteit Utrecht

www.freudenthalinstituut.nl

www.stralenpracticum.nl