Ab

1. Absorption of γ-rays – Determination of the Half-value Thickness of Absorber Materials

1.1 Introduction

In this exercise we work with weak radioactive sources in order to learn about how radiation is attenuated by different materials. This is important knowledge for those who design radiation shields, intended to protect the human organism in controlled situations where radiation is employed to perform desired tasks, such as in medicine, or nuclear power plants, and unwanted exposure must be avoided. It may also be the necessary knowledge to protect human life from nuclear explosions in a situation of warfare.

The atomic nucleus consists of protons and neutrons, bound by forces making up a complicated internal structure determined by a set of discrete energy levels. Just as for the atomic electrons, the energy levels represents quantum mechanical states into which the nucleus can be excited by absorbing energy while in a lower state, or by emitting energy from a higher excited state. In both ways energy is exchanged in discrete amounts corresponding to the difference in energy between the levels involved in the process. The energy exchanged is in the form of electromagnetic waves, or mass particles with kinetic energy, and most often, a combination of both.

The notion of *radioactive decay* is understood here as the process by which an unstable, excited atomic nucleus spontaneously decays by emitting particles and radiation. The terms 'decay' and 'disintegration' are used with the same meaning, the latter being historically motivated by the early observation, that an atom actually 'disappeares'. In fact, as we shall see below, the given *chemical species* disappears, but reappears as different species, a process generally known as *transmutation*. This term, again, has a wider notion than what is covered in this text.

Radioactive decay is a random process at the atomic scale, in the sense that it is impossible to predict when any single atom will decay, but as we shall see, the *average* decay rate for a population of like atoms is predictable. Related to this is the half-life $T_{1/2}$, which is the time it takes for a population of a certain radioactive atom to decrease by a factor of $1/2$. As is demonstrated already here, we will often use the word 'atom' when actually 'nucleus' is meant.

An excited nuclei may decay by one or several of a number of processes, the best known being

emission of an α or a β-particle, internal conversion, fission - and γ-decay. Most processes involve only the nucleus, but some includes the atomic electrons. While the other modes of decay involves particle emission, γ-decay proceeds through emission of a photon, i.e. a quantum of electromagnetic radiation. Particle emission is almost always followed by γ-emission as part of the decay, since it is unlikely that particle emission alone will take the parent nucleus down to a stable state.

γ-radiation, sometimes also called γ-rays, is electromagnetic radiation of very short wavelength ($\lambda < 10^{-2}$ nm), emitted when energetically unstable atomic nuclei decay. A nucleus that will eventually decay by emitting excess energy as radiation of any kind is said to be *radioactive*, meaning that it is existing in an excited state and has not yet decayed). The phenomenon is called *radioactivity*.

X-rays and γ-rays both stand for electromagnetic radiation. Various earlier attempts have been made to define a difference in usage, but the most consistent way is to refer to X-rays when the radiation comes from processes involving atomic electrons, and γ-rays when the radiation comes from the nucleus. We shall prefer to use the word γ-photon or γ-quantum here.

γ-radiation is present everywhere on Earth as a background of natural radiation, coming from space or the decay of natural radioactive isotopes contained in rocks and soils. This natural radioactivity is of only minor importance for radioactive safety, since the intensity is low, except in a few locations. Still, amateur mineral collectors should be aware of the potential health hazards they risk by harbouring collections in their homes over long periods of time. See the appendix for some examples of natural radioactivity.

Effects of radiation damage in human tissue and other materials have been thoroughly investigated, and extensive knowledge collected to estimate limits for radiation exposure.

The object of the present laboratory is to show the principles of protection through radiation shields. This requires knowledge about the energy dependence of the absorption properties of the shielding material. The properties of lead, aluminium and water will be investigated. γ-radiation sources with energies of 0.66, 1.17 and 1.33 MeV will be used.

Below we speak of γ-radiation, γ-quanta, and sometimes γ-rays, which all refer to the same phenomenon.

General safety considerations

Do not unnecessarily remove the cap (an aluminium pin) from the sources. Do not expose any part of your body to the radiation from the opened sources. Avoid touching the unpainted lead slabs. Do not drink and eat in the laboratory.

1.2 Theory

a) Gamma ray sources

Gamma rays are electromagnetic radiation emitted as quanta (photons) of characteristic energy. An atomic nucleus may exist in any of a large number of excited quantized energy states, most of

which are unstable in the sense that the nucleus will decay by emission of excess energy to some lower state, which may by a stable, or another unstable state, in which case a cascade of γ-photons is emitted.

The process by which the nucleus is lifted to the excited state is not of concern here, but it may be through activation, e.g. bombardment with neutrons, or the nucleus may be a member of any of the long lived natural decay chains, that survive since the formation of the Earth.

A radioactive nucleus may decay from an excited energy state E_i to a lower state of energy E_f. The difference $\Delta E = E_i - E_f$ is the energy of the photon: $E_\gamma = \Delta E$

The wavelength λ and frequency ν of the photon is related to the energy as:

$$E_\gamma = \frac{h \cdot c}{\lambda} = h\nu \tag{1.1}$$

where

$$h = \text{Planck's constant} = 6.626 \times 10^{-34}\,\text{Js} \tag{1.2}$$
$$c = \text{speed of light} = 2.99 \times 10^{8}\,\text{m/s} \tag{1.3}$$

The energy (or alternatively the wavelength) of the γ-radiation emitted, is a characteristic of a certain nucleus, although alternative decay modes exist for some nuclei, and may be used to identify the nuclei of an unknown radioactive source. This may also be put to advantage in activation analysis, where the nuclei of a sample are deliberately activated to make them produce their 'signature' radiation. In this way, often using neutron activation, trace elements in a sample may be identified. The radiation is typically in the range of 100 keV to several MeV. The unit eV (electron volt) is a unit of energy, which by definition is equal to the amount of kinetic energy acquired by a single free electron passing through an electrostatic potential difference of one volt in vacuum.

$$1\,\text{eV} = 1.602\,176\,565 \times 10^{-19}\,\text{J}^{1} \tag{1.4}$$

Obviously, the eV is not a SI unit, but it is accepted for use with the SI. The eV is for practical reasons widely used in many branches of physics, and is written with SI prefixes.

In the present laboratory two sources of γ-radiation are used: a ^{60}Co and ^{137}Cs.

The decay scheme of both processes is shown in Fig. 1.1. In both cases the decay consists of a chain starting with emission of an electron, *beta minus decay* (β^-). This leaves the daughter nucleus in an excited state, from which it decays through emission of one or more γ-quanta.

On a more fundamental level, in weak interaction a neutron (n) is converted to a proton (p) while emitting an electron (e^-) and an antineutrino ($\bar{\nu_e}$):

$$n \rightarrow p + e^- + \bar{\nu_e} \tag{1.5}$$

[1] Exact value of the elementary charge due to new SI conventions as of 2018.

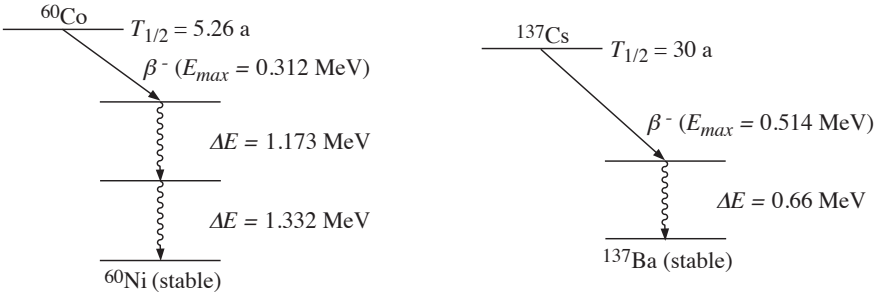

Abbildung 1.1: Decay scheme ^{60}Co (left) und ^{137}Cs (right).

The initial β^-decay involves a transmutation: The daughter nucleus is a new atomic species with atomic number one unit higher - in the case of cobalt: nickel; in the case of cesium: barium. The initial daughter nucleus is in both cases also excited, and decays through subsequent emission of γ-photons, which are the sources of the radiation we utilise in the experiments.

The decay scheme, as depicted in Fig. 1.1, may be thought of as having a vertical axis in energy, which is not drawn to scale. Horizontally there is an implied atomic number axis. This is seen in that the β^-decay proceeds one unit to the right, meaning that the daughter nucleus has one more proton, but still the same number of nucleons, A. Consequently β^+ decay would be drawn as going to the left.

$$^{137}_{55}\mathrm{Cs} \rightarrow ^{137}_{56}\mathrm{Ba} + e^- + \bar{\nu_e} \tag{1.6}$$

$$^{60}_{55}\mathrm{Co} \rightarrow ^{60}_{56}\mathrm{Ni} + e^- + \bar{\nu_e} \tag{1.7}$$

In the case of ^{60}Co, after the initial β-decay, the emission of a γ-photon does not take the nucleus down to a stable state, but to an intermediate state, an excited Ni nucleus, which with very short delay decays to the stable Ni nucleus. In this process, therefore, two γ-rays are emitted almost simultaneously. We will not attempt to separate them, but rather determine the attenuation for the mixture of the two energies.

b) Radiation attentuation

Quantum theory offers two different views on the concept of radiation: The electromagnetic wave model, or the corpuscular model.

The corpuscular model envisages the energy exchanged in an excitation or de-excitation as a process where a particle carries the energy involved in the transition. This model is suitable for scattering processes.

In the wave model energy is exchange, by a quantum, or wave packet of energy $E_\gamma = \Delta E$. This model is better suited for absorption processes since we are interested in the continuous attenuation of the radiated energy.

The different physical processes that attenuates γ-radiation are summarised in the appendix.

In order to obtain a formula suitable for calculating the attenuation, we first assume we have a thin slab of an absorber of thickness $d\,x$, cf Fig. 1.2. The slab is placed between the source and the detector, which are assumed to be in line with each other, as in Fig. 1.5. We further assume the number of quanta that will not reach the detector to be proportional to the thickness of the slab and the number of quanta $N(x)$ impinging on the slab. The constant of proportionality is the *attenuation coefficient* μ. In a simplified assumption the quanta are either absorbed, or scattered out of the beam. Then we may write:

$$dN = -\mu \cdot N(x) \cdot dx \tag{1.8}$$

$$\frac{dN}{N} = -\mu \cdot dx \tag{1.9}$$

The magnitude of the attenuation coefficient μ depends on the material of the absorber plate, and the energy of the radiation. Since the number of quanta passing through the slab by necessity must be lower than $N(x)$, a negative constant is required. The negative sign for the coefficient is a convention, applied in order to make μ a positive material constant - we would not like to tabulate negative material constants.

Solving the differential equation 1.9 we have

$$N(x) = N_0 \cdot e^{-\mu \cdot x} \tag{1.10}$$

where N_0 denotes the number of quanta at $x = 0$. Equation 1.10 shows that the intensity of the γ-radiation behind the absorber declines exponentially and therefore never exactly vanishes.

For radiation protection design, a commonly specified entity is the *half-value thickness*, which characterises suitable materials for any particular type of radiation and the energy involved. As the name indicates, this number directly gives the thickness required to reduce the intensity of the incoming radiation by half. (cf Fig. 1.3). For calculations, the more fundamental *attenuation coefficient* μ is preferred, which of course, is related to the half-value thickness cf equation 1.12

$$\frac{N_0}{2} = N_0 \cdot e^{-\mu \cdot d_{1/2}} \tag{1.11}$$

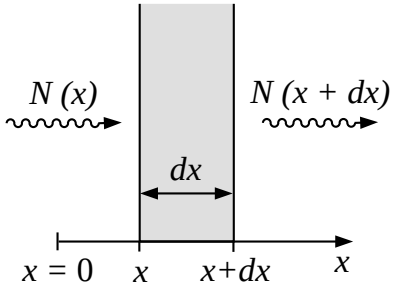

Abbildung 1.2: Attenuation of γ-radiation in a thin layer of an absorber.

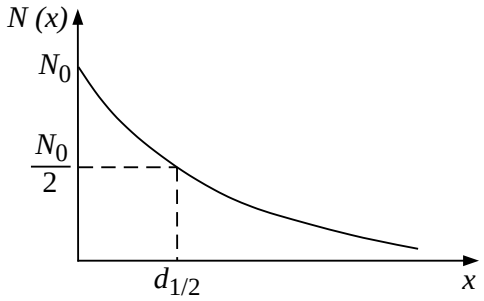

Abbildung 1.3: Determination of the half-value thickness $d_{1/2}$.

$$d_{1/2} = \frac{\ln 2}{\mu} \tag{1.12}$$

Just as for the $d_{1/2}$, μ depends on the material of the absorber and the energy of the radiation. Some examples for γ-radiation may be found in Table 1.1.

Tabelle 1.1: Examples of half-value thicknesses in cm

	Lead	aluminium	Air	Water
0.1 MeV	0.014	1.7	3.6×10^3	4.1
0.5 MeV	0.41	3.0	5.9×10^3	7.3
1 MeV	0.88	4.3	8.3×10^3	9.9
2 MeV	1.36	5.7	13.4×10^3	17.3
5 MeV	1.46	9.5	21.5×10^3	21.7

1.3 Experimental

a) Principles of the measurement

In order to determine the half-value thickness of an aborber, the intensity of the γ-radiation is measured as function of the absorber slab thickness. The number of γ-quanta penetrating the absorber in a chosen interval of time, Δt, is counted with a *Geiger-Müller-tube* or counter (GM tube). It suffices here to understand that the GM-tube counts γ-quanta that ionise gas atoms in the tube.

Limitations are that not all quanta can be counted: Only those entering the counting volume could be counted at all, essentially a geometrical problem (the tube has a window, often at the short end of the tube that is particularly easily penetrated by the radiation); some quanta will escape from the counting volume without ionizing the gas; thirdly, some will ionize the gas at an instant when another quanta already has done so a short time interval before - the dead time - during which the detector is blind for new events. There is also a threshold for the energy that will ionize the gas. Since we are not making absolute measurement, no corrections are undertaken.

The working principle of the GM-counter is explained briefly: Some intermediate process is needed in order that a quantum can be registered. In essence, a γ-quantum (a mass-less bundle of energy) causes an electron to be expelled from an atom of a suitable, easily ionisable gas. This electron has enough kinetic energy to further ionize other gas atoms, creating an avalanche of free electrons, an amount of charge that can be electronically converted to a voltage pulse, amplified and counted. The pulses are accumulated during the counting time set, and for this reason it is common to speak about *pulses* counted.

Taking the logarithm of both sides of equation 1.10 yields

$$\log_{10} N(x) = \log_{10} N_0 - \mu x \cdot \log_{10} e \tag{1.13}$$

Correcting $N(x)$ for background counts U, and using semi-logarithmic graph paper, $\log N(x) - U$ plotted against the absorber thickness x yields a straight line with slope a:

$$a = -\mu \cdot \log_{10} e \tag{1.14}$$

from which the attenuation coefficient μ and the half-value thickness $d_{1/2}$ may be calculated (cf Fig. 1.4).

b) Experimental set-up

The experimental equipment is outlined in Fig. 1.5. The radioactive sources are encapsulated in thin metal shields that absorb the β^--radiation accompanying the decay. The γ-radiation is only slightly attenuated, but the β^--radiation, for all practical matters, will not penetrate, and not be detected, not even when the intensity of the source is measured without absorber.

Each source is contained in a cylindrical lead radiation shield in order to reduce health hazards below tolerable levels. The shield has a cylindrical bore through which the radiation is collimated in the direction of the counter. The purpose is to protect persons working in the laboratory. The counter is likewise mounted in a lead shield, but in this case to shield the counter from unwanted radiation from outside: cosmic rays, natural radiation from the environment, radiation incorporated in building materials or radiation scattered in the laboratory.

The absorber plates to be evaluated are placed between the source and the detector, as shown in Fig. 1.5.

Thicknesses of the absorbers used:

- Pb: 4 mm (1 slab)
- Al: 20 mm (1 slab)
- Water: 10 cm (length of cylindrical container)

c) Experimental procedure

- Inquire of the lab assistant the details of how the GM-counter works and how it should be handled.
- Inquire of the lab assistant the time intervals to be used for the different measurements.
- Put away the sources as far from the line of sight of the detector opening as possible. Measure the background counts for the given time interval three times.
- Place the shield with the source to be used first in the setup as intended. Then remove the cylindrical pin that seals the source. Do not expose yourself or any part of you body to the radiation from the bore in the shield.
- Count the background pulses without absorber in the beam ($x = 0$) for the counting time specified. Then insert the first lead slab and count the corresponding pulses. Add another slab and continue the series of measurements till all 10 slabs are mounted.

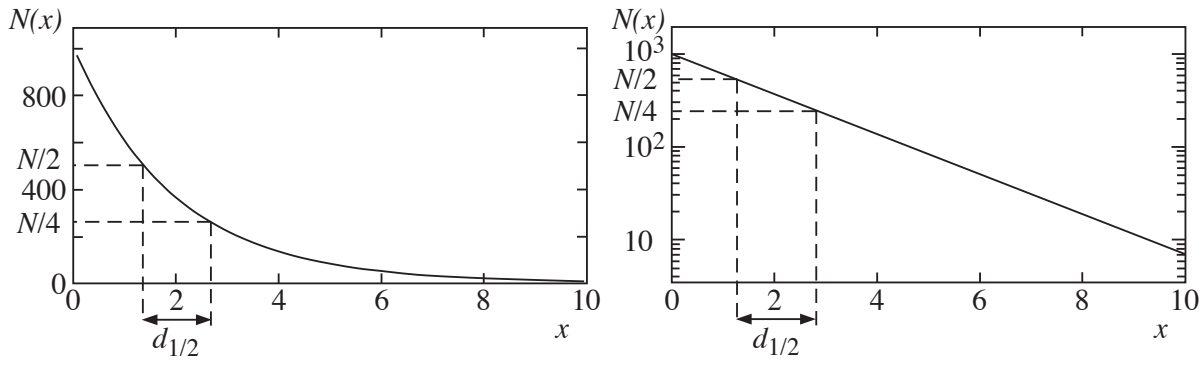

Abbildung 1.4: Determination of the half-value thickness $d_{1/2}$.

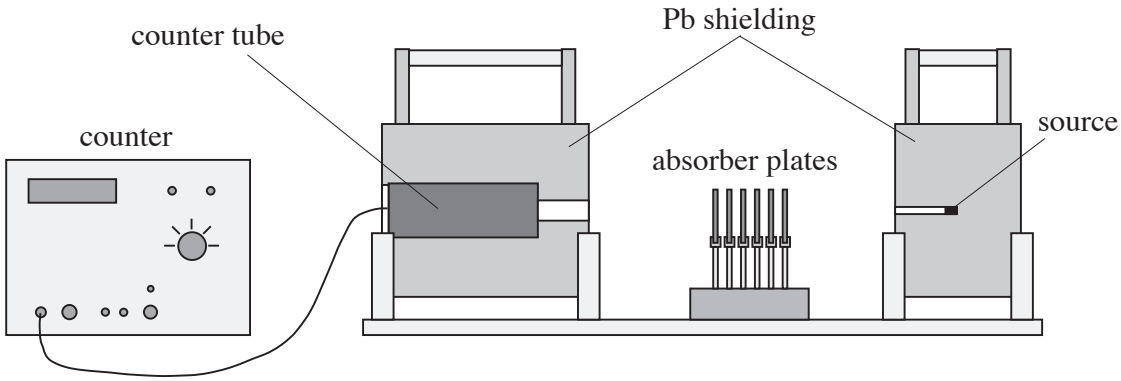

Abbildung 1.5: Experimental set-up.

- Remove all the lead slabs and repeat the measurement series for the 5 aluminium slabs.
- Remove the aluminium slabs and mount the Plexiglas cylinder filled with demineralized (deionized) water, not tap water. Since radiation is absorbed also in the Plexiglas cylinder end windows, a measurement is also required to correct for the empty tube.
- Repeat the entire sequence of measurements above using the other of the two sources.
- Finally, perform a measurement in order to verify the statistics of the pulse counting (cf. Data evaluation). Use the ^{137}Cs source and mount a single lead slab between source and GM-tube. Count the pulses for 1 s, and repeat 50 times.
- Collect all data in a comprehensive table.

d) Data evaluation

Determination of the half-value thickness:

- For each series of measurement, plot *by hand* and on semi-log graph paper (provided) the number of counts N for a given time interval as function of absorber thickness x. Do not forget to subtract the background count U. Draw error bars for each point. The statistical error for a single measurement is:

$$m_N = \sqrt{N} \tag{1.15}$$

and

$$m_U = \sqrt{U/3}\,. \tag{1.16}$$

You may verify the latter formula by error propagation. The number of counts after subtraction of the background is denoted as $N'(x)$:

$$\begin{aligned} N'(x) &= N(x) - U \\ m_{N'} &= \sqrt{m_N^2 + m_U^2} = \sqrt{N + U/3} \end{aligned} \tag{1.17}$$

- Estimate by eye the straight line that best fits the data points (cf Fig. 1.6) and draw it in the diagram, then determine the half-value thickness $d_{1/2}$.
- In addition to the best fitting straight line, draw the steepest and the flattest straight line that is compatible with the the error bars, and evaluate their respective slope. From this, estimate the maximal error in $d_{1/2}$.
- Determine the slope of the line from the plot and calculate the absorption coefficient (no error analysis required).

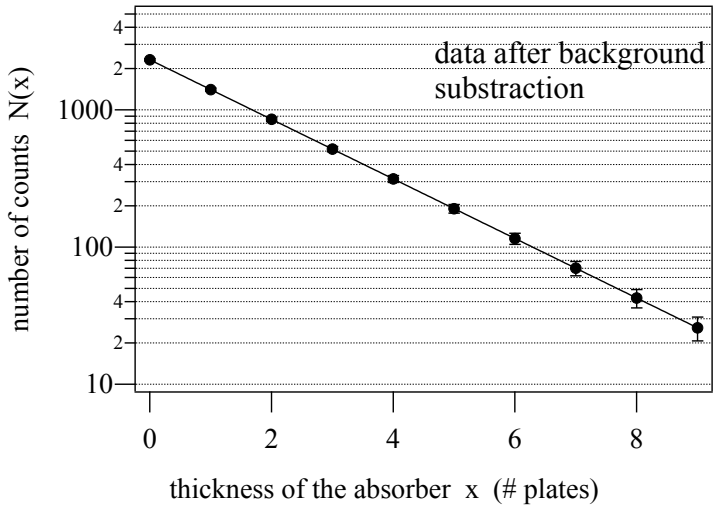

Abbildung 1.6: Best fit of a line to an exponential function in semi-log representation.

Further assignments:

- Calculate the thickness of the slab of lead that would attenuate the γ-radiation by a factor of ten.
- From the measurements on the water filled cylinder, calculate the attenuation factor for 10 cm of water. Also, calculate the thickness of lead and aluminium that would be necessary to attain the same attenuation.
- According to equation 1.15, the statistical scatter (standard deviation) of a number of pulses N is $m_N = \sqrt{N}$. Verify this relation using the series of 50 measurements. Determine the mean value and the standard deviation. Compare the result with the expected value $m_N = \sqrt{N}$.

1.4 Appendices

1.4.1 Radioactivity in everyday life

News reports mentioning radioactivity in whatever connection cause interest and fear alike. Radioactivity appears in many forms and on many different occasions; it may be associated both with desirable features and devastating consequences. Here we summarise just a few instances where radioactivity is often encountered.

Natural sources of radiation

Natural radioactivity emanates from the few isotopes that have decay times long enough for them to survive since the formation of Earth. There are a few to be found in different places of the periodic table, but the most important belong to the three main *decay chains* that exists in nature. Decay starts with ^{232}Th, ^{238}U, and ^{235}U, respectively, and known as the *thorium series*, the *radium series* (sometimes uranium series), and the *actinium series*. At the end of these chains stand different, stable isotopes of lead. The chains contain sequentially decaying radioactive isotopes. As a consequence, there is a build-up of radioactivity that may become much higher than any single isotope alone. Uranium is not very active, but the common uranium mineral pitchblende may contain substantial activity.

Radon is often heard of in connection with radiation hazards. Different isotopes of it are contained as members of all three decay chains. Radon (Rn) is an inert gas, which means that it can escape from the rocks and soils where it is produced, and e.g. accumulate in houses built on ground containing the natural decay series. Hence the gas may be inhaled and reside for a while in the lungs. The gas may very well be exhaled, in particular since it is an inert atom and not likely to bind to lung tissue. The radon isotopes have short half-lifes, except ^{222}Rn in the radium series, which has $T_{1/2}$=3.8 days. All radioactive radon isotopes in the chains decay by emission of an α-particle. This heavy particle (actually a helium nucleus), would be stopped by the superficial layer of the skin (epithelium). In the lungs, though, an α-particle can cause considerable damage. The α-particle have high energy, but is still not the most serious problem with radon: Radon decays to polonium, and later in the chains appears bismuth, tellur and and lead isotopes, many of which decay by α-emission, as is often the case with radioactive heavy elements. If the radon nucleus decays in the lung, the daughter nucleus is not gaseous and the subsequent decays in the chain all take place in the lung. In this sense radon serves as the vehicle that transport radioactivity into the lung.

Potassium is a less well known source of natural activity, and certainly less of a problem. There are two stable isotopes, ^{39}K (abundance 93.3%) and ^{41}K (6.7%), and there is one naturally occurring radioactive isotope: ^{40}K (0.012%). Potassium is contained in the bones of mammals, but the small abundance is enough to make ^{40}K the largest source of radioactivity, more so than ^{14}C, in healthy animals and humans – yes, humans are living sources of radioactivity: in a body of 70 kg mass, about 4,400 nuclei of ^{40}K decay per second, equivalent to an activity of 31 Bq/g. The isotope ^{40}K has a half-life of 1.250×10^9 a, and is subject to a branched decay to stable ^{40}Ar (11.2%) by electron

capture and positron emission, and to stable ^{40}Ca (88.8%) by beta decay. The decay of potassium to argon is a common method for dating geological formations and for so called weathering studies. Potassium is also used as a tracer element in studies of nutrient cycles.

The decay of ^{40}K to ^{40}Ar is the prime source of atmospheric argon: after oxygen the third most abundant gas in Earth's atmosphere, 0.93%.

In certain types of concrete building materials a content of ^{40}K contributes to the radiation background, but this is mainly of concern for measurements that require a very low background count.

Artificial sources

In this category we find such diverse sources of radioactivity as tests and actual use of nuclear warheads, scientific and medical applications, or accidents because of neglectful handling.

Radiation protection is of little importance for natural sources, but becomes crucial for man-made sources, since these may be quite intense, and pose extensive health hazard. Among such sources are waste from nuclear industrial operation, mainly nuclear power plants, but also from use of radionuclides in medicine, for research or therapy.

γ-radiation exposure in medicine comes from the use of X-ray cameras or the more sophisticated X-Ray tomography technique (Computer Tomography, (CT)). Cancer therapy use γ-radiation to destroy tumors, either by radioactive needles inserted into the tissue (e.g. activated gold needles), or through directed radiation sources outside the body (^{60}Co). these sources are produced by irradiation in nuclear reactors, and may pose considerable radiation hazards of improperly handled, either during use, or after disposal. Several gruesome accidents involving irresponsibly disposed medical ^{60}Co sources are known.

The other source we use in this lab, ^{137}Cs, happens to be one of the worst artificially produced contaminants. This is because of its long half live of 30 years, but most importantly because it is produced in huge amounts in nuclear explosions or nuclear power accidents. This was demonstrated in the Chernobyl accident, when the isotope spread over large part of Europe, and entered the biosphere either into plants or animals that fed from such plants, making milk, fish, meat from grazing animals, and crops grown on fields or in the woods toxic for many years. ^{137}Cs is one of the most prominent fission products resulting from uranium fission, being at

Another important fission product appearing together with cesium is ^{131}I, which accumulates in the thyroid gland. This is the reason why iodine pills are stored for the case of a nuclear accident: the gland is saturated with normal iodine so that it will absorb less of the radioactive ^{131}I.

Other artificial sources not to forget are radar and other microwave equipment. An improperly manipulated kitchen microwave oven may pose considerable hazard.

1.4.2 Dosimetry

Radiation is a natural part of our habitat, and the essence of radiation safety is to protect from any unnecessary or too high levels of radiation. Radiation safety is a sophisticated science, which for

different parts of the human body and for human organs prescribe which is a tolerable dose level. In practice, the thickness of an absorber is chosen so that protection for the particular application is adequate.

a) Source strength

The source strength, or *activity*, Q of a radioactive source gives the rate of disintegration $[s^{-1}]$: the number of excited (radioactive) nuclei decaying per second. Q is defined as the total number of radioactive nuclei present multiplied by the *decay constant* λ, the probability that a nuclei decays during the next unit of time (second).

The SI-unit is Becquerel: 1 Bq being the activity when 1 nucleus decays per second. Then we have:

$$Q = \lambda \cdot \frac{N_A \cdot m}{A} \tag{1.18}$$

where

$$\begin{aligned} Q &= \text{source strength [Bq]} \\ \lambda &= \text{decay constant [s]}^{-1} \\ N_A &= \text{Avogadro number} \approx 6.023 \times 10^{26}\,\text{kmol}^{-1} \\ m &= \text{mass of the source in kg} \\ A &= \text{atomic mass of the isotope [kg/kmol].} \end{aligned}$$

b) Ionizing radiation exposure (for γ-radiation or X-rays)

When γ-radiation or X-rays penetrate an absorber, they lose energy mainly through interaction with the electrons of the atoms of the absorber. The result is a free electron and an atomic ion, known as an *ionic pair*. The *ionizing radiation exposure* is a measure of the number of ionic pairs created in one kg of air, given as electric charge per kg.

Unit for ionizing radiation exposure: 1 C/kg

The roentgen (R) is an older, traditional unit that should not be used, but may still be found. 1 R is the amount of radiation required to liberate 1 esu of charge of each polarity in 1 cubic centimeter of dry air. 1 Roentgen = 2.58 $\times 10^{-4}$ C/kg dry air.

c) Absorbed dose

Ionizing radiation inflicts damage on materials penetrated, in the sense that atoms may be displaced, or molecular bonds broken. The former is important when it comes to electronics used e.g in satellites, the latter for biological tissue and important molecules such as DNA.

The amount of damage done to matter by ionizing radiation, is better related to the amount of energy deposited rather than the charge. This is the *absorbed dose* (also known as total ionizing

Tabelle 1.2: Quality factors QF for selected types of radiation

Kind of radiation	QF
γ-radiation	1
β-radiation	1
fast neutrons and protons	≈ 10
slow neutrons	≈ 3
α-particles	≈ 15
heavy ions	≈ 20

dose, TID). It is the energy deposited per unit mass of the medium, unit J/kg, and given the name Gray (Gy).

The absorbed dose is the amount of radiation required to deposit the energy of 1 joule in 1 kilogram of any kind of matter through ionizing processes. The unit is Gray, in the SI defined as:

$$1\,\text{Gray} = 1\,\text{Gy} = 1\,\text{Joule/kg} = 1\,\text{J/kg}$$

The equivalent older unit is **rad** (Roentgen absorbed dose), which is 0.01 J deposited per kg: 100 rad = 1 Gy.

c) Equivalent dose

The biological impact of radioactive radiation is of particular importance, but is not well described by the absorbed dose: 1 Gy of α-radiation would cause more damage to a biological sample than 1 Gy of γ-radiation. To compensate for this, appropriate weighting factors can be applied, which reflect the different relative biological effects: this is the *equivalent dose*. As a measure for the biological impact the unit Sievert was introduced, which is compatible with the SI through:

$$1\,\text{Sievert} = 1\,\text{Sv} = 1\,\text{J/kg}$$

The unit 1 Sievert is defined as the amount of radiation absorbed by the human body that generates the same biological impact as 1 Gy X-ray radiation with energy 200 keV. This the so called *equivalent dose*, which is calculated from the absorbed dose and a *quality factor* QF, cf table 1.2:

$$\text{equivalent dose [Sv]} = \text{QF} \times \text{energy dose [Gray]}$$

d) Older units – summary

More information on units may be found with The International Commission on Radiation Units and Measurements (ICRU), a standardization body set up in 1925 by the International Congress of Radiology.

Until about 1985 a set of older units were in use:

Source strength	1 Curie = 1 Cu = 3.7×10^{10} Bq
Ionizing radiation exposure	1 Röntgen: = 2.58 $\times10^{-4}$ C/kg air
Absorbed dose	1 rad = 10^{-2} Gy
Equivalent dose	1 rem = 10^{-2} Sv

d) Typical radiation exposure

The radiation exposure of humans through natural sources varies between locations. A total mean estimated for an entire population is:

- 0.3 - 0.6 mSv/a radiation of cosmic origin, and
- 0.4 - 1.5 mSv/a from from the ground

Natural radiation exposure from the earth depends on the local occurrence of radionuclides in soils and rocks, and may vary substantially. A typical value for Germany is 0.4 mSv/a, but in Ramsar, in Iran, 6 mSv/a is measured. Natural exposure from cosmic radiation increases with height. In Berlin (Germany) (20 m above sea level), 0.3 mSv/a; in La Paz (administrative capital of Bolivia, east of Lake Titicaca at an altitude of 12,001 feet (3658 meters)), 2.0 mSv/a.

Cosmic radiation gives an additional exposure that is not negligible. The exposure during one flight from Europe to North America is roughly the same as the equivalent dose from an X-ray investigation of the extremities. Assuming 10 days in one year at typical transatlantic flight altitudes of 35,000 to 39,000 feet above sea level, the additional exposure amounts to 1.4 mSv/a.

Increased exposure may also come from building materials, if they are made from rocks that contain natural occurring isotopes. The use of granite or slag bricks (scoria) for construction, increases the exposure with up to 2 mSv/a.

In comparison, the exposure because of medical X-ray diagnostics amounts to about 2 mSv/a.

1.4.3 Interaction of γ-rays with matter

The attenuation of γ-radiation penetrating a sample occurs mainly through three distinct processes: the photoelectric effect, pair production and Compton scattering. Which of these effect is domination depends on the energy of the incident γ-photon.

a) The photoelectric effect

When a γ-photon interacts with the electrons of the atoms in the absorber, the energy of the photon may be transferred to an electron, which is either excited to a higher bound atomic state, or, if the energy of the photon is higher than the binding energy, the electron is expelled from the atom; the atom is ionized and a free electron created. For increasing photon energies, electrons of lower lying states (harder bound) can be expelled. As the energy increases beyond the threshold energy

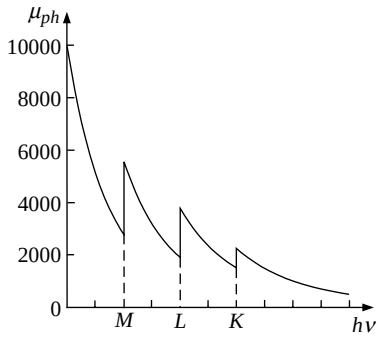

Abbildung 1.7: Absorption curve for photoelectric effect.

for exciting electrons in a deeper lying shell, the total probability for absorption increases stepwise, and it is customary to speak of the K, L, M edge in a diagram of absorption coefficient against photon energy, cf 1.4.3).

If the atom is ionized, the free electron is expelled with (kinetic) energy:

$$\frac{m_e \cdot v^2}{2} = h\nu - E_B \tag{1.19}$$

where

$$\begin{aligned} h\nu &= \text{Energy of the } \gamma\text{-photon} \\ \nu &= \text{Frequency of the } \gamma\text{-radiation} \\ h &= \text{Planck constant} = 6.626 \times 10^{-34}\,\text{Js} \\ E_B &= \text{Binding energy of the electron} \\ m_e &= \text{Rest mass of the electron} = 9.109 \times 10^{-31}\,\text{kg} \end{aligned}$$

The attenuation coefficient μ_{Ph} for the photoelectric effect is proportional to $Z^5/(h\nu)^3$. The photoelectric effect dominates for smaller γ-energies and heavy absorber atoms.

b) Pair production

Pair production refers to the creation of an electron and its antiparticle, in our case from a photon, but the process is also more general. The process is only possible above a certain threshold energy for the γ-photon, the total rest mass energy of the two particles ($h \cdot \nu > 2 \times 511\,\text{keV}$). In addition, the process cannot take place with a single photon alone: it is possible close to a nucleus (photon-nucleus pair production) where the electrical field of the nucleus couples to the particles involved. A photon-photon pair production is also possible [2].

[2]For the photon-photon pair production process each photon should possess the electron rest mass energy 511 keV in the center of the momentum frame. For the photon-nucleus process the photon is required to carry the entire electron pair rest mass energy 1.022 MeV.

The attenuation coefficient for pair production is proportional to:

$$Z^2 \cdot \log\left(\frac{2\,h \cdot \nu}{m_e \cdot c^2}\right). \tag{1.20}$$

Attenuation through pair production dominates at high γ-energies.

c) The Compton effect

Compton scattering, or the *Compton effect*,[3] is an inelastic scattering process between an incident γ-quantum of energy $h \cdot \nu$ and a bound electron with zero momentum and energy [4]. In effect, the quantum is scattered in another direction with a lower energy, $h \cdot \nu'$, and longer wavelength, λ'. The wavelength change $\lambda' - \lambda$ is known as the *Compton shift*. Part of the energy lost by the photon is transferred to the electron, part to the atom (cf Fig. 1.8). After the scattering the electron travels under angle φ_1 relative to the incident photon, and the photon is scattered an angle φ_2 with an energy $h \cdot \nu'$.

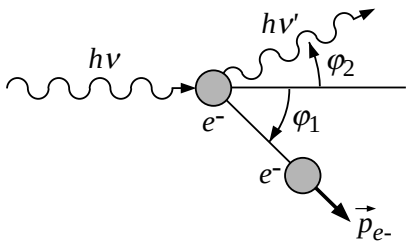

Abbildung 1.8: Geometry for Compton scattering with energies for the two photons and momentum for the scattered electron given. The host atom is not shown.

We then have for the energy of the scattered photon (it is always smaller than the energy of the incident photon):

$$h \cdot \nu' = \frac{h \cdot \nu}{1 + \frac{h \cdot \nu}{m_e \cdot c^2} \cdot (1 - \cos\varphi_2)} < h \cdot \nu \tag{1.21}$$

The corresponding expression for the wavelengths may be written on the form:

$$\lambda' - \lambda = \frac{h}{m_e \cdot c} \cdot (1 - \cos\varphi_2) \tag{1.22}$$

The attenuation coefficient μ_c for the Compton process is proportional to the nuclear charge Z of the absorber. Compton effect is dominating for γ-energies 1 MeV to 10 MeV, between the ranges where the other γ-processes dominate.

[3] The Compton effect was observed by Arthur Holly Compton in 1923, who was awarded the 1927 Nobel Prize in Physics for the discovery.

[4] *Nuclear compton scattering* is also known, as is *Inverse Compton scattering*.

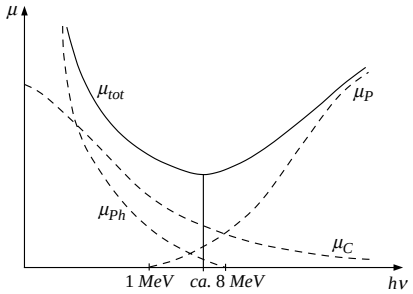

Abbildung 1.9: Absorption curves for γ-radiation.

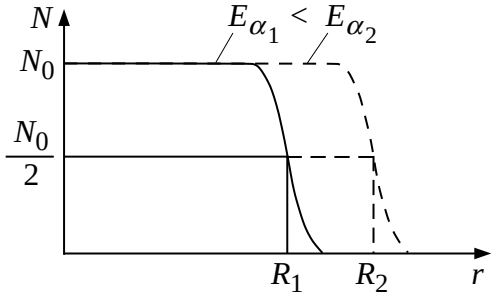

Abbildung 1.10: Range of α-particles.

d) Total attenuation coefficient

The attenuation of γ-radiation by matter (an absorber) is a combination of the three processes discussed above. The attenuation as function of energy for the three separate processes as well as their total attenuation is shown in Fig. 1.9 for lead.

1.4.4 Absorption of alpha and beta radiation

a) Alpha radiation

Alpha particles are ^{4}He nuclei, consisting of 2 neutrons and 2 protons that may form as a particularly stable configuration in an excited nucleus, and leave with considerable kinetic energy in a decay process. The *range* of a particle is defined as the distance penetrated in a material sample by incident radiation. The range will depend on the kind of particle incident, the energy, and the properties of the absorber material. The range is, apart from small statistical variations, a number that can be tabulated, cf Fig. 1.10, where the number of penetrating α-particles are shown as function of absorber thickness. As an example, the range of 5 MeV α-particles in air is about 4 cm.

b) Beta radiation

Beta particle (electrons) dissipate energies while penetrating an absorber through coulomb interaction with the electrons of the atoms of the absorber. The particles also collides with nuclei and

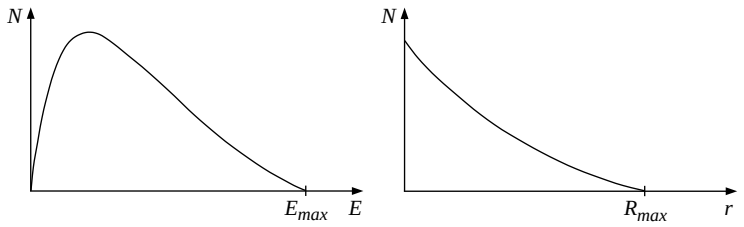

Abbildung 1.11: Energy spectrum the range of β-particles.

Tabelle 1.3: Maximum energy in MeV for some β-sources and maximum range in mm in some absorber materials

β source	$E_{\beta_{max}}$	Range R_{max}		
		Air	Water	Lead
^{3}H	0.018	3	4×10^{-3}	3.5×10^{-4}
^{14}C	0.115	270	0.35	3.1×10^{-2}
^{35}S	0.167			
^{203}Hg	0.214	350	0.45	4×10^{-2}
^{131}I	0.606	1550	2.0	0.2
^{32}P	1.71	5430	7.0	0.6

change momentarily the direction in elastic collisions (no energy loss). The actual distance travelled is thus far longer than the range of the particle. The electrons emitted from a β-source have a continuous distribution of energy, as shown in Fig. 1.11. The maximum energy E_{max} is characteristic for the decaying nucleus.

The number of β particles penetrating through the absorber as function of the absorber thickness is roughly described by an exponential function (cf Fig. 1.11).

In Table 1.3 Collected ranges R_{max} for different absorber materials for some β-sources.

It is common to give the range also in g/cm^2 or mg/cm^2 instead of cm. Then:

$$\text{range in g/cm}^2 = \frac{\text{range in cm}}{\text{density of the absorber in g/cm}^3} \tag{1.23}$$