Introduction to Radiation Protection for the Radioactive Physics Practicum

UNI Basel
Physics Institute
Radiation Protection
D. Sacker
Translation: Avigail Abuhatsira

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Introduction:

The wide application possibilities of ionizing radiation was discovered directly after the discovery of the ionizing rays more than hundred years ago by W. C. Röntgen (1845-1923), H. A. Becquerel (1852-1908) and Madam Curie (1867-1934). During the time followed by this discoveries these 'wondrous' rays were used without protection precautions, not only in research, technology and medicine, but also for the entertainment of the astonished public. As the initial and accumulative damages of radiation was acknowledged, stricter guidelines and regulations for contact with ionizing radiation were forced, first by the radiologists and later by the 'international committee for ray protection '.

In the Federal Constitution **article 24** is concerned with radiation protection. In it, there is the radiation protection law **StSG,** and the radiation protection regulation **StSV.** Progresses, which take place in radiation protection, supplement new regulation. The radiation protection law and the radiation protection regulation are summarized in the green booklet with the name radiation protection. The present valid version is from 1 October 1994.

Ionizing radiation in general:

Absorbed dose (energy dose) D:

Radiation sources send out energy. If this radiation energy comes across an absorber *e.g.* a 'tank' with distilled water, the rays are absorbed by the water, which is warmed by the energy absorption. The unit for the 'absorbed dose' is the Gray. 1 Gy is the dose, which results from a spatially constant energy flux density during the transmission of 1 joule of homogeneous subject of the mass 1 kg (*e.g.* water) from ionizing radiation.

1 Gy = 1 J/kg

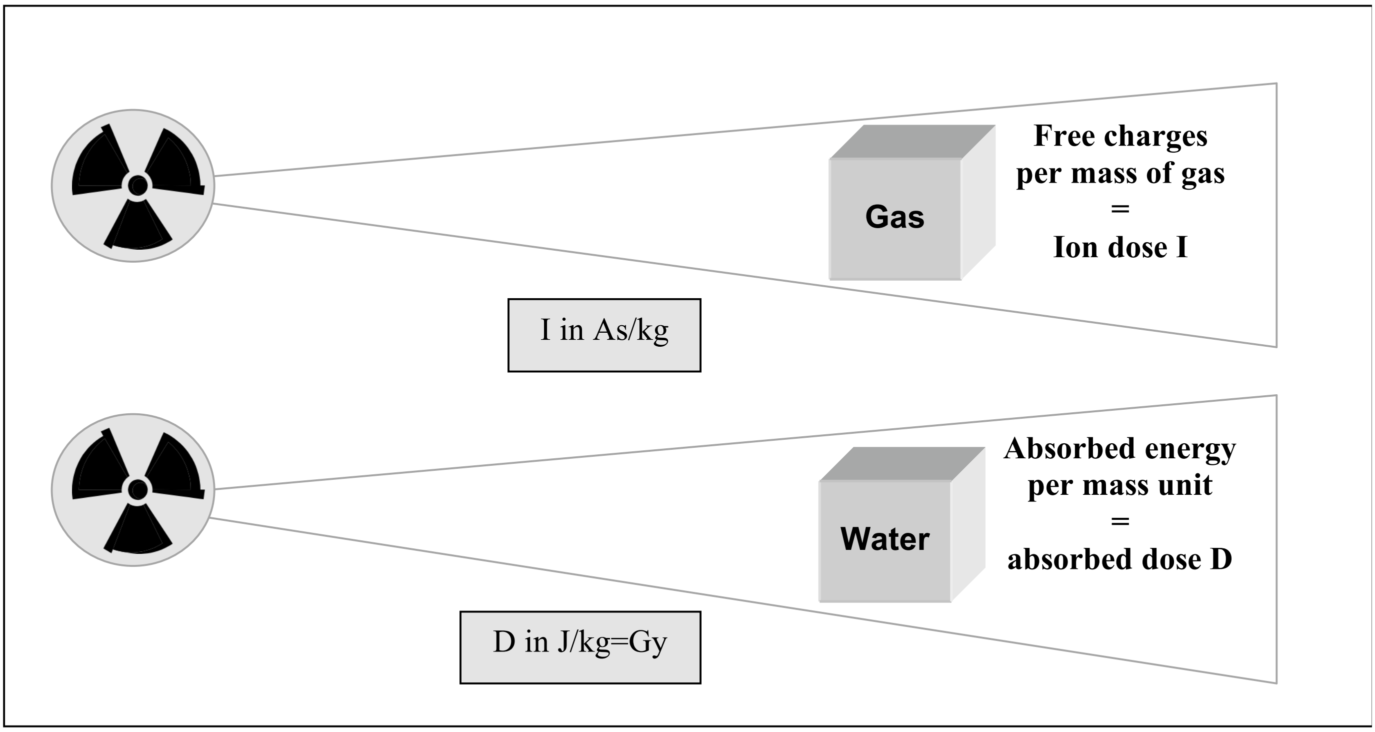
Size	New unit	Old unit	Conversion
Absorbed dose	Gray [Gy]	Rad [Rd]	1 [Gy] = 100 [Rd]

Apart from the absorbed dose one knows also the **absorbed dose rate D°**. It has the unit Watt by kg **[W/kg]; 1 [W/kg] = 1 [Gy/s]** (hardly ever used). The common unit is the **[Gy/h]**.

- The dose rate of a radioactive source can be compared with the amount of water for a time unit flowing from a spring. <u>The longer one stands in a radiation filed</u> with a certain dose rate, <u>the largest is the accumulated dose!</u>

The dose rate is the dose per time unit *e.g.* hours **h** or years **y**.

D° = D / t



<u>Ion dose:</u>

The ion dose arrives from the charged particles (electrons, ions) in a gas volume produced by ionizations. Ion dose is measured by charge for a certain gas volume. If one knows the energy required to separate an electron form an atom, the energy deposited in this volume can be calculated. The Ion dose is given in *Coulomb by kg* **[C/kg]** (As / kg).

Size	New unit	Old unit	Conversion
Ion dose	[C/kg]	Röntgen [R]	1 [C/kg] = 3876 [R]

The equivalent dose H

In contrast to the absorbed dose D the equivalent dose H refers **to the impact** of the ionizing radiation **on humans**. As the different kinds of rays cause the human body different dangerous damages, a **priority factor WR** (or **WBR)** was introduced. The new unit was called Sievert **[Sv]** and the equivalent dose H is given by:

H = D * WR

H = equivalent dose in Sievert **[Sv]**
D = absorbed Dose in Gray **[Gy]**

The priority factor for the different radiation kinds is:

Radiation Kind	WBR
X-ray	1
γ -radiation	1
β - radiation	1
α - radiation	20
Neutrons (E = 10keV...100keV und 2MeV...20MeV)	10

see ray protection regularities from 1994, page 57

Size	New unit	Old unit	Conversion
equivalent dose	Sievert [Sv]	[rem]	1 [Sv] = 100 [rem]

The **equivalent dose rate H°**, is measured in Sievert per a time unit, usually **[uSv/h]** or **[mSv/h]**.

The effective dose E

If only a certain organ is exposed to the ionizing radiation, the effect is naturally smaller than if the whole body was exposed to the same radiation. Therefore, another **priority factor WT** (Tissue Weight) was introduced for the different organs, the result was called the **effective dose E**. The total number of these priority factors for all organs **sums to 1**. The unit is again the **Sievert**, and the corresponding formula is:

E = H * WT = D * WR * WT

E = effective Dose in **[Sv]**
H = equivalent dose in **[Sv]**

How harmful is the ionizing radiation for humans?

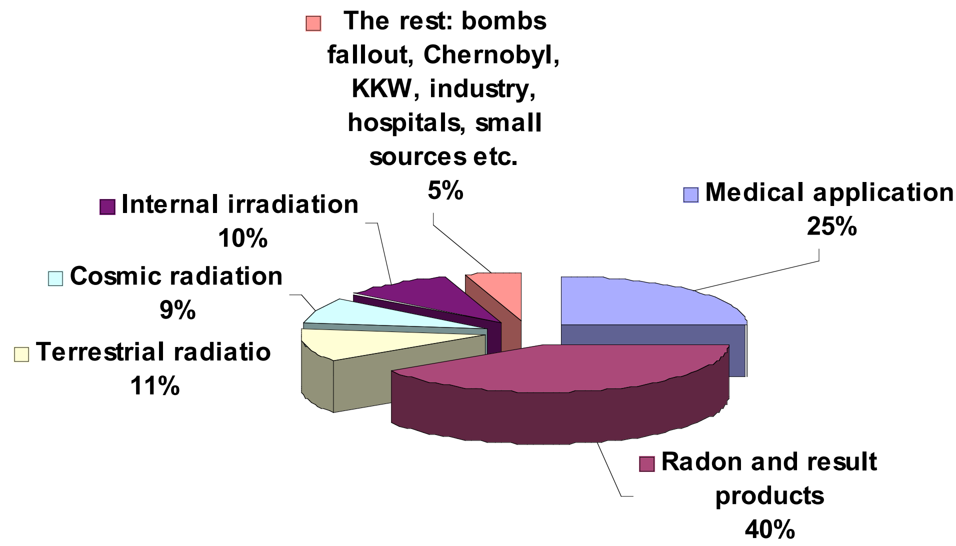
Epidemiological studies show that accumulating a total dose of **1 Sievert** during the years, gives a **4%** probability of getting cancer. Since on average about 20-25% of the people die of this illness, these 4% add themselves to the average. It is important to add that 1 Sievert is a very high dose, a **maximum dose of 20 mSv/y** is accumulated by people from the lines of work, which requires the use of radioactive materials. However, the radiation decision- authority would intervene on the account of dosimeter supervision, a long time before these 20mSv would be accumulated.

What have we learned about the ionizing radiation?

- When radiation from a radioactive source is stopped in an absorber we know the **absorbed dose D in Gray [Gy].**

- As not all ray kinds cause identical damage in the human tissue, the **equivalent dose H** was introduced in Sievert which corrects the absorbed dose with a priority factor **WBR** accordingly. The equivalent dose refers to a whole body exposure.
- The **effective dose E,** for the irradiation of only a single organ, is given through the consideration of the **organ priority factor WT**.
- As long as we work **only with X-rays, β - rays und γ -rays,** one can equate **Gray and Sievert**.

To what kind of rays are humans exposed in their surroundings?



This diagram gives an overview of the average radiation exposure of the Swiss population. it sums up to be about **4 mSv per year**. We distinguish three equally important parts, namely:

- Cosmic and terrestrial irradiation load, which comes by purely natural influences.
- The radon load, which has indeed a natural origin, but is strongly influenced by civilization conditions (a kind of the house block).
- Irradiation, which is registered only from the use of radioactivity and ionizing rays. The dose from medical diagnostics is the most important portion of this load.

Radon:

The noble gas Radon-222 develops from Uran-238 in the interior of the earth over different nuclides. As noble gas radon is chemically no longer bound, and can penetrate into cellars and houses, depending upon gas permeability of the rock and the building ground, where it accumulates. Breathing the contaminated air carries the radon into the lungs. The α-particles emitted from the radioactive decay irradiate the tissue and can release cancer. (smoke represents however a far larger risk than radon). The radon concentration can reach values to 10000 Bq/m^3. The average value in Swiss houses is 60 Bq/m^3. The limit value according to the radiation protection regulation is 1000 Bq/m^3. One can find high radon concentrations in the Tessin, Engadin and Hochjura.

Terrestrial radiation:

The earth-rock contains uranium as well as its daughter nuclides. Since the rocks in the Alpine contain more uranium then the central country, higher terrestrial radiation is registered in the Alps.

Cosmic radiation:

High energy radiation particles (protons and alpha particles) from the sun and other stars collide with atomic nuclei (nitrogen and oxygen) as they arrive into the mantle of air of the earth and destroy them. In doing so, new particles and nuclei are created, these new particles and nuclei will continue to fly until their energy is depleted. On the ground only the radiation, which results from various secondary processes, can be observed. . The dose rate from cosmic irradiation depends on the height above sea level. . During intercontinental flights (approximately 10km height) the dose rate from cosmic rays adds to an average of **5 uSv/h**, with maximal values up to **13 uSv/h**. The flight crew gets the average effective dose of **3 mSv per year**.

Irradiation by incorporation:

The natural radioactive nuclei K-40 enters the body through food, where it contributes the biggest share of radiation with 3 to 4,5 kBq (the K-40 activity depends on the muscle mass). On the other hand, the isotopes of the natural decay chain of uranium, thorium *et al.* as well as the isotopes C-14 resulting from interaction in the atmosphere contribute only a small share to the incorporation.

Irradiation by artificial radioactivity and ionizing rays:

This contribution originates to the smallest part from: the incorporation of Cs-137 and Sr-90 from nuclear weapons tests and the reactor accident in Chernobyl, krypton-85 from reprocessing plants of core fuel rods, tritium from nuclear weapons tests and from the luminous paint industry, I-131 from hospitals, argon-37 from underground nuclear weapons tests and from nuclear power plants. Some mushrooms growing in the Ticino still have a Chernobyl related activity of up to 5,5 Bq/g of fresh weight.

Small sources (such as clocks with luminous digits) and the polonium-210 inhaled by smokers cause a larger contribution than the above civil and military uses.

A large dose originates from **medical diagnostics and therapy**. A single lung x-ray adds on average a 0,2 mSv lung dose, which corresponds to an effective dose of approximately 24 uSv.

In the context of artificial radiation one should also mention the more than 60000 people in Switzerland, which are exposed to radiation at their workplace. In average, such a person receives 0,12 mSv per year (1998).

- The natural radiation in Switzerland on average amount to approximately 0.1 uSv/h. Therefore, if a value of 1.0 uSv/h is measured with a Geiger-Müller counter, one would say that the radiation is about 10 times higher than the background.
- If we would take an overseas flight which takes, for example, five hours, we would accumulate 5 * 5 uSv/h = 25 uSv. If, at that time we would have stayed home, we would have accumulated only 5 * 0,1 uSv/h = 0,5 uSv.

Radioactive Sources

Activity of Radioactive Sources

One indicates the activity of a radioactive source in Becquerel **[Bq]**. The old unit for it is curie **[Ci]**. Activity is a measure of the number of radioactive atoms, which decay in one second in a radioactive source. 1 Bq = 1 decay per second.

Size	**New unit**	**Old unit**	**Conversion**
Activity	Becquerel [Bq]	Curie [Ci]	1 [Bq] = 27[pCi] 1 [Ci] = 37[GBq]

Ray Energy

Radiation produces its effects through disposing its energy. The energy of the radiation is measured in electronvolt **[eV]**. **1 eV** is the energy of a single electron as it is accelerated in an electric field of **1volt**.

α -Radiation:

What is α-radiation?

α-radiation is a **particle radiation** in which helium nuclei are emitted. As the α -particles fly through air they react to form helium. For this reason, the range of the α -particles is limited in air to only **a few centimeters**, where the α -particles uniform energy cause a sudden end in their reach.

How can one protect himself from α -radiation?

α **-radiation** can loose all its energy when going through the thinnest folios, for example **paper**, or at most, **cardboard**. Although, α -particles can not penetrate through the upper layer of the skin, and thus are harmless compared with other kinds of radiation, it can, however, cause **severe damages** when **ingested or inhaled** due to the particles **high energy**.

Radiation	**Range**	**Shielding**
α	up to 5cm	paper, cardboard

β -Radiation:

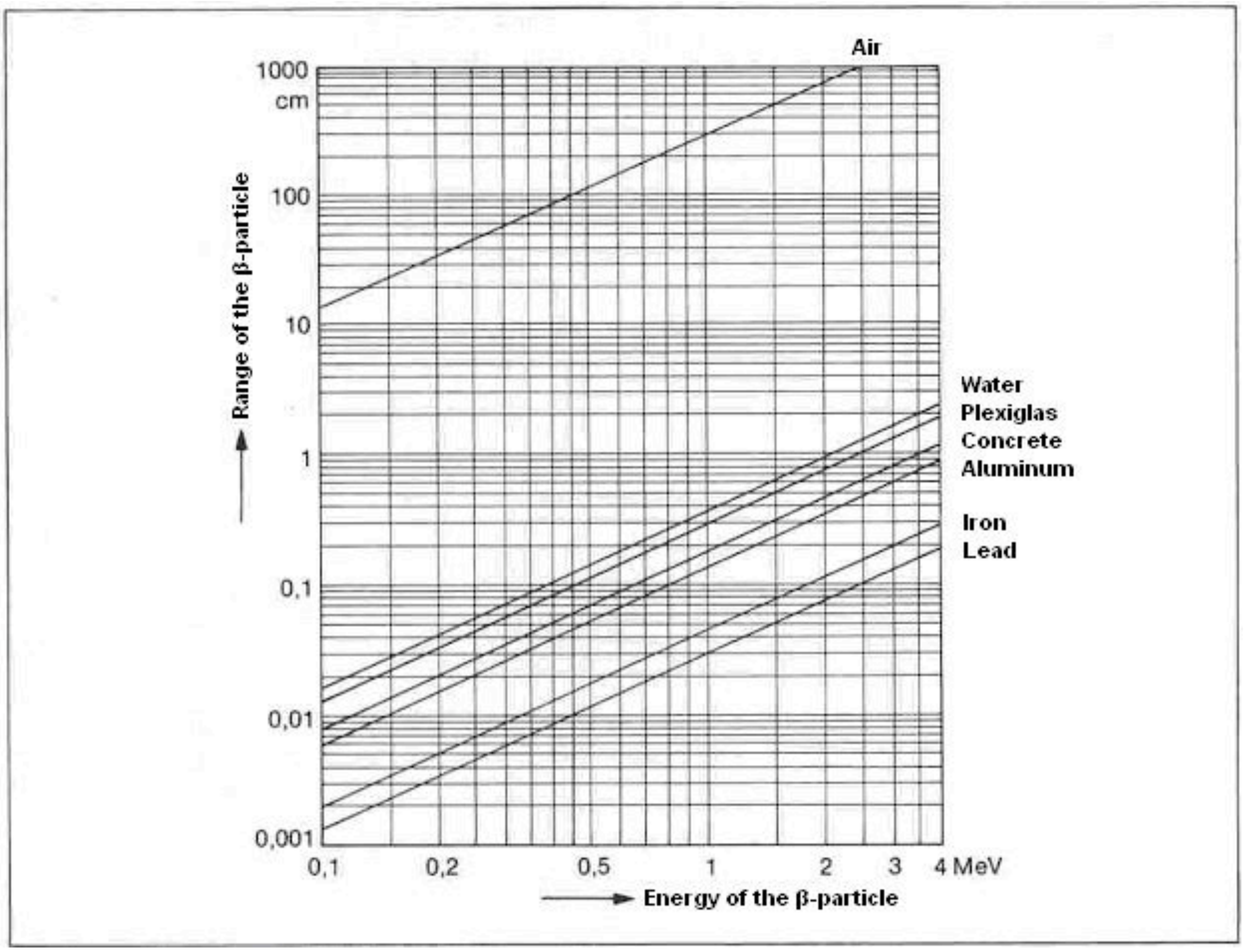
What is β -radiation?

β **-radiation** like the α -radiation this a **particle** radiation. β -particles are emitted electrons, which also form bonds in air, therefore their range is not infinite. Because the energy of β -particles is on a continuous spectrum, and therefore not all β -particles have the same energy, the intensity decreases with growing distance from the source, not following the Square Distance Law, but depending on the type of nucleus. One can however say that **near the source the ray intensity is a lot higher than it would be after the square distance law**. Therefore **one should not touch a** β **-source with the hands** if possible. The range of the β -radiation can be, depending on the energy, up to **8 meters**.

How can one protect himself from β -radiation?

One can be completely shielded from β -radiation using **1 cm of glass or Perspex**, or **5 mm of aluminum**. High energy β -particles can easily penetrate the horn layer of the skin and damage the underlying layer. Therefore skin burns can occur with a high β -dose. However, β -particles can not penetrate deep into the body and, thus, cannot cause any direct organ damages.

The graph bellow describes the **maximum range** of β -particles in **cm** as a function of their energy.



One should use an element with a low **atomic number** *e.g.* Perspex (also know as acrylic glass) with Z=6 as **shielding** from β-radiation, because a shield with a high atomic number will produce *bremswaves* (x-ray) as the β particles are absorbed.

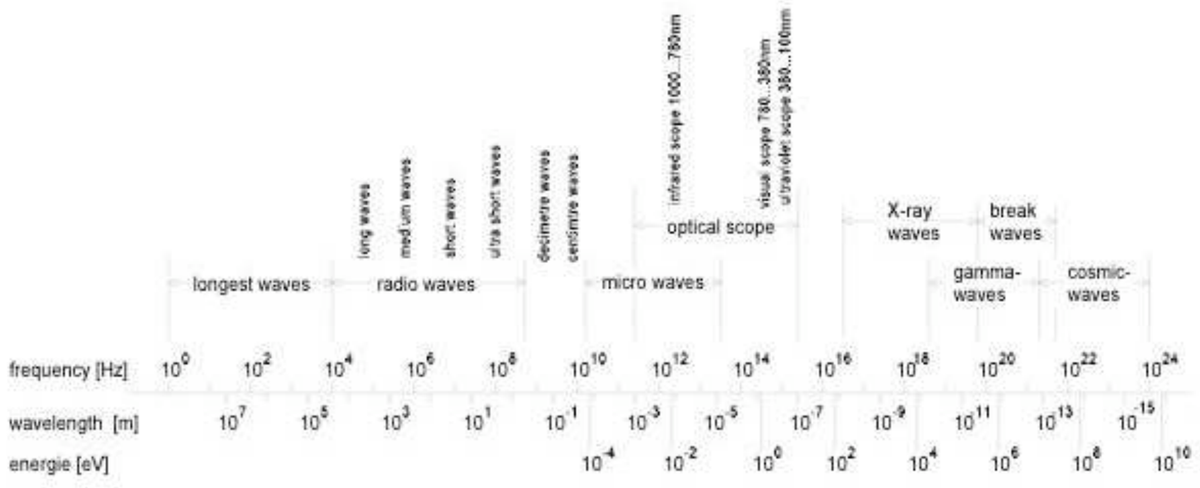
Radiation	**Range**	**Shielding**
β	up to 8 Meter	0,5 cm Aluminum, 1 cm Plexiglas

If only a partial weakening of the β-radiation is desired, it can be calculated using the weight per surface and the density of the absorber (see the appropriate practicum experiment).

Photons-Radiation:

What is photon radiation?

Photon radiation is a **wave radiation**. It has thereby an **electromagnetic energy**. The photons wavelength is between **10^7 and 10^{-15} meters**. The energy of the photon radiation depends on the photons wavelength. The visible light is only a small range in this far spectrum. Wavelength of the visible light lies between 780 and 380 nm. The energy in this range is of the order of 1 eV. The photon radiation follows the **square distance law** and their **range is infinite**.



What is γ -Radiation?

γ **-radiation** is a subrange of the **photon radiation** with short wavelength and thus high energy, γ -radiation has a **wavelength of between 10^{-10} to 10^{-13} m** which corresponds to energy values between **10 keV to 10 MeV**.

γ **-radiation** is penetrating, it can penetrate deeply into the body and damage organs. The γ **-radiation** is the main one responsible for the external radiation dose.

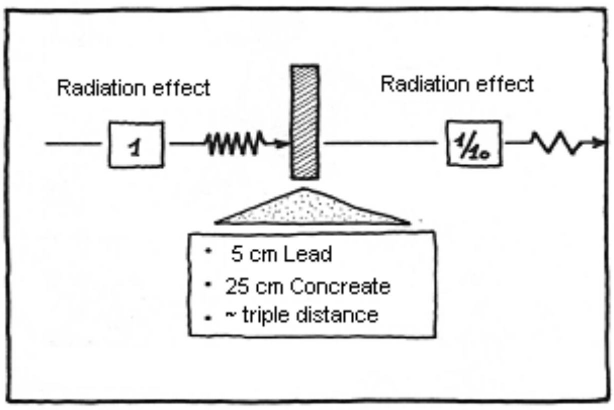
How can one protect himself from γ -radiation?

γ -radiation can be weakened but not fully stopped. In contrast to β -radiation one have to use an element with a high atomic number as a shield (*e.g.* **lead** with a Z=82) for the weakening of the γ -radiation.

What is the half or tenth value weakening?

As one can only weaken the γ -radiation we introduce to new terms; the tenth value weakening **ZWS** and the half value weakening **HWS**.

Tenth value layer:



What is the square distance law?

According to the square distance law, the photon radiation becomes weaker with increasing distance from the source. (double distance = 1/4 of the radiation, triple distance = 1/9 of the radiation.)

$$D2° = D1° * \left(\frac{r1}{r2}\right)^2 \qquad r2 = r1 * \sqrt{\frac{D1°}{D2°}}$$

D1° = Dose rate in distance **r1** from the source
D2° = Dose rate in distance **r2** from the source

What should one choose as an absorber?

The thickness of the absorber which leads to the appropriate weakening depends on the energy of the γ -radiation. In the table bellow you can find the thickness of the tenth value weakening, and half value weakening layers as a functions of the radiation energy in the most important absorption materials.

Energy MeV	Water HWS (cm)	Water ZWS (cm)	Concrete HWS (cm)	Concrete ZWS (cm)	Iron HWS (cm)	Iron ZWS (cm)	Lead HWS (cm)	Lead ZWS (cm)	Uranium HWS (cm)	Uranium ZWS (cm)
0,1	21	30	4,7	8,2	0,8	2,1	0,1	0,3	0,03	0,07
0,2	27	45	7,6	14,6	1,3	3,4	0,2	0,55	0,05	0,10
0,3	28	51	9,9	19,7	1,8	4,5	0,3	0,9	0,08	0,26
0,4	28	54	11,3	23,7	2,3	5,4	0,4	1,3	0,15	0,50
0,5	28	57	12,3	25,8	2,6	6,2	0,5	1,6	0,22	0,75
0,6	27	57	12,4	26,8	2,8	6,8	0,7	2,1	0,30	1,0
0,8	27	60	12,6	28,4	3,2	7,8	1,0	3,05	0,52	1,6
1,0	28	62	12,9	29,9	3,4	8,5	1,3	3,8	0,67	2,0
1,5	28	70	13,6	34,0	3,8	10,0	1,7	5,1	0,90	2,7
2,0	30	78	14,1	37,6	4,0	11,0	2,0	5,9	1,1	3,3
3,0	34	88	15,3	43,4	4,4	12,2	2,1	6,5	1,2	3,6
4,0	35	97	16,4	47,5	4,2	12,5	2,0	6,4	1,2	3,5
6,0	39	115	18,8	51,6	4,1	12,7	1,6	5,5	1,0	3,1
8,0	41	124	18,8	52,8	4,0	12,6	1,5	4,9	0,85	2,8
10,0	41	131	18,8	54,0	3,8	12,0	1,35	4,2	0,8	2,6

How do I calculate the dose rate after the installation of a shield?

For a given absorber, one can calculate the dose rate with shield as shown bellow:

$$D°(d) = \frac{D°(0)}{10^{\frac{d}{ZWS}}}$$

D°(0) = Dose rate without shielding **[uSv/h]**
D°(d) = Dose rate with shielding **[uSv/h]**
d = Thickness of shield **[cm]**
ZWS = Lenth value layer thickness **[cm]**

How do I calculate the absorber thickness?

One can calculate the absorber thickness directly for obtaining a reduced dose rate, if the dose rate without a shield is already known.

$$d = \log\left(\frac{D°(0)}{D°(d)}\right) * ZWS$$

Radiation	**Range**	**Shielding**
γ	infinity	material with high atomic number *e.g.* **lead**

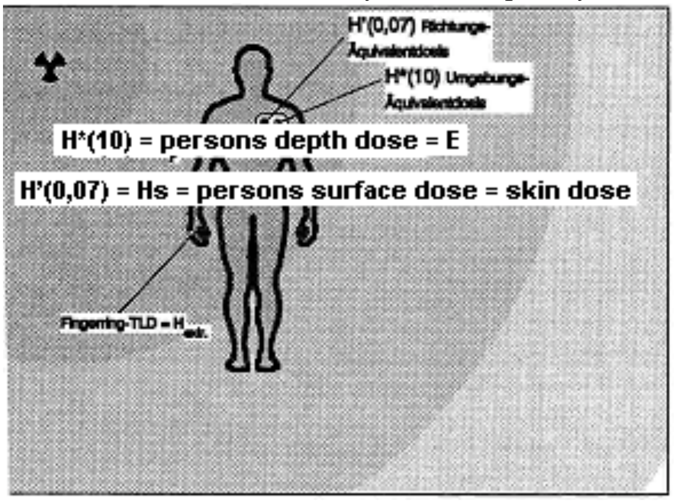
What have we learned about radioactive sources?

- The **activity** of a radiation source depends on the number of radioactive atoms, which decay in one second. One measures the activity of a radioactive source in Becquerel [Bq].

  - The **energy** of a radioactive source is measured in electronvolts [eV]. 1 eV is the energy of a single electron as it accelerates in an electric field of 1 Volt.
  - α **-rays** have a range of only a few cm in air. Paper can be used as a shield. As directly irradiating source they are harmless for humans. However, due to incorporation they are dangerous as well, because of their high energy.
  - β **-rays** have a range of a few meters in air. For a shield one can use aluminum or Perspex. As direct irradiating source they are particularly dangerous for the skin, especially in short distances from the source.
- γ **-rays** reach infinitely far. Their reach is given by the square distance law. One can not stop them, but only weaken them. At best one can use lead shielding. They are penetrating and can damage organs.

Dosimeter Monitoring

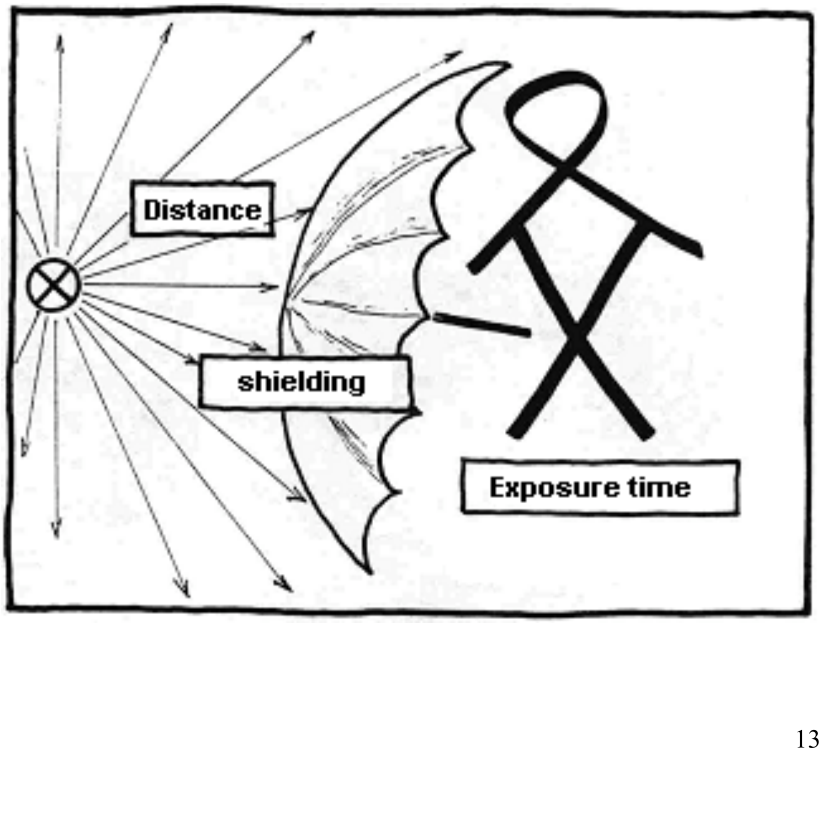
In the radioactivity practicum, it is **obligatory** to use the **red house dosimeters**. The dosimeters contain two **TLD**'s (thermal luminescence dosimeters), which are small Lithium Fluoride crystals. One crystal is for the β **-rays** and the other for the different γ **-rays**. The crystal used for the β -rays measurements is located behind a 0,07 mm thick PVS layer, which simulates the skin. The crystal used for γ -rays measurements is located behind an aluminum layer, which simulates a 10 mm tissue layer; consequently, the measured dose is comparable to the skin dose or effective dose, respectively. We assume that a person is standing in a homogeneous radiation field with his whole body, therefore the effective dose is assumed to be equal to the depth dose Hp.



The evaluation of the TLD's takes place with internal equipment. The exited electrons from the radioactive source do not fall immediately to the valance band in the crystals, but are held in the forbidden energy gap (trapped electrons). One would have to heat the dosimeter to a temperature between 200 to 400 °C to restore the electrons to their original position by transmission of light. The quantity of light is proportional to the dose with which the crystals have been irradiated. The quantity of light is counted with a photoscintillator. The **detection limit** is about **0.01 mSv**.

The Four Rules of Radiation Protection

If working with a radioactive source, the basic three rules of radiation protection apply: ⇒



If working with an open source, we also have to care about **respiratory** protection, in addition to the other three protection methods in the picture, because of the danger emanating from incorporation. Therefore always work under a vent!

Calculation of Different Doses and Dose Rates

Attached in **appendix 3** is the **radiation protection regulation (StSV**) table with *data for the **operational radiation protection***. The table contains all the radioactive nuclides and data regarding the calculation of different quantities.

- The column **h10** allows the calculation of doses and dose rates for a defined distance to a **known γ -source** with a known activity.
- The column **h0,07** allows the calculation of doses and dose rates in a distance of 10 cm from a **known β -source** with a known activity.
- The column **hc0,07** allows the calculation of **contamination** with a known **open radiation source** (powder or liquid one buried)

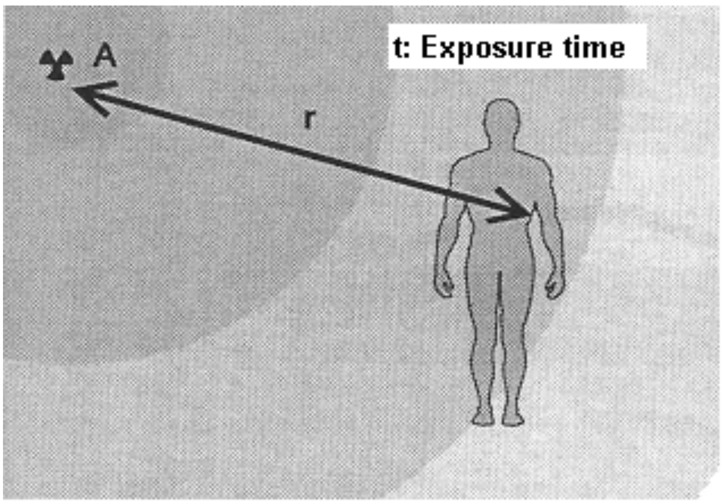
There are additional columns for the calculation of radiation limits, with or without the need of approval, and recommended radiation levels, which we will not treat in this course. These are quantities for handling open radioactive sources in the radiation lab, which are used in research and production.

How do I calculate the γ -radiation of a known source?

X-rays and γ -rays penetrate deeply into the a human tissue, therefore, the dose is determined at **<u>10 mm</u>** depth. γ -radiation is calculated using the square distance law.

$$Hp = A * t * h10 * \left(\frac{1m}{r}\right)^2$$

$$Hp^\circ = A * h10 * \left(\frac{1m}{r}\right)^2$$



Hp°	= **Equivalent penetrating dose rate H** in [**mSv/h**]
Hp	= **Equivalent penetrating dose H** in [**mSv**]
A	= Activity in [**GBq**]
t	= Time in **hours** [**h**]
h10	= Dose depth in [**(mSv/h)/GBq**] (Radiation protection regulation- appendix 3)
r	= Distance from the radiation source in **Meters** [**m**]

Example:

If a man is standing for **two hours** in a distance of **0,5 Meter** from a **Co-60** source with an activity of **5 MBq** . What will be the equivalent dose **Hp**?

$$Hp = 0{,}005GBq * 2h * 0{,}366mSv/h * \left(\frac{1m}{0{,}5m}\right)^2 = \underline{0{,}0146mSv}$$

Calculation of the activity from a measured dose or dose rate:

For calculating the activity from a dose or dose rate, one should convert the formula for Hp:

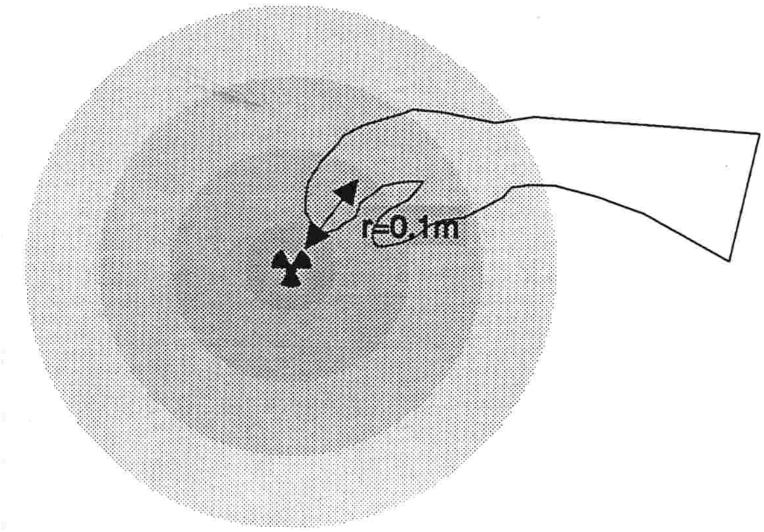
$$A = \frac{Hp}{t} * \frac{1}{h_{10}} * \left(\frac{r}{1m}\right)^2 = Hp° * \frac{1}{h_{10}} * \left(\frac{r}{1m}\right)^2$$

How do I calculate the β -radiation of a known source?

The β -radiation barely penetrate the skin. therefore, the dose rate is determined at a tissue depth of **0,07 mm** (the subcorneuos layer of the skin). Accordingly, this dose is called **surface dose** or **skin dose**.

Hs° = A * h0,07

Hs = A * t * h0,07



Hs°	= **Equivalentdose surface rate H** in [**mSv/h**]
Hs	**= Equivalent dose surface H** in [**mSv**]
A	= Activity in [**GBq**]
t	= Time in **hours** [**h**]
h0,07	= Surface dose in **[(mSv/h)/GBq]** (Radiation protection regulation- appendix 3)

β -radiation **does not** spread according to the square distance law, thus the distance is not contained in the formula. The distance is established in the formula as **10 cm**. **Examining sources which emit β and γ rays we find, that over short distances, the portion of β -rays outbalances the portion of γ -rays by over two orders of magnitude.**

Example:

If someone is standing for half an hour in the vicinity (10 cm) of a C-14 source, which has an activity of 100 MBq. What will be the skin dose?

Hs = A * t * h0,07 = 0,1GBq * 0,5h * 200(mSv/h)/GBq = 10mSv

Distances different than 10 cm:

If the distance is not 10 cm, there is a correction which can be carried out. this correction, however, is not very exact.

$$Hs = A * t * h0,07 * \left(\frac{0,1m}{r}\right)^2$$

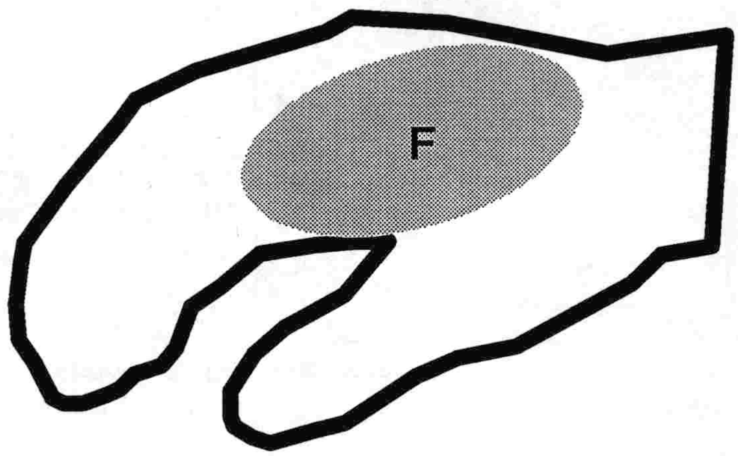
r = Distance in Meter [**m**]

If the distance is **smaller than 0,1 m**, the result is probably **overrated**. If the distance in **bigger than 0,1 m**, the distance is probably **underrated**. One must calculate only up to the maximum reach of the β-radiation of the appropriate nuclide.

Contamination

While working with open radiation sources (powders or fluids), spilling of these will cause radioactivity to be spread on surfaces, or even on the skin or on clothes of co-workers. This is generally called contamination.

α and weak β -rays, do not penetrate the skin dipper than **0,07 mm**, thus do not cause **Hs**. However, these rays are still not completely harmless as there are still incorporation dangers.



The activity **A** per surface **F** is called surface contamination **A/F**. It causes an equivalent dose in the skin depth of **0,07 mm** of:

$$Hs° = \frac{A}{F} * hc_{0,07}$$

$$Hs = \frac{A}{F} * t * hc_{0,07}$$

Hs° = Contamination equivalent dose rate in [**mSv/h**]
Hs = Contamination equivalent dose in [**mSv**]
A = Activity in [**kBq**]
F = Surface in [**cm^2**]
t = time in **hours** [**h**]
hc0,07 = Contamination factor in [**mSv/h / kBq/cm^2**] (StSV appendix 3)

Example:

If someone has a contamination on the back of his hand with an activity of 1 MBq, for two hours from a P-32 source. What is the equivalent dose?

(The surface of the back of the hand is 100 cm^2)

$$Hs = \frac{A}{F} * t * hc_{0,07} = Hs = \frac{1000kBq}{100cm^2} * 2h * 1{,}6 \frac{mSv/h}{kBq/cm2} = \underline{32mSv}$$