Abstract

Radiation protection is a preliminary to any exposure to ionizing radiation. The so-called ALARA radiation-safety principle is based on the minimization of radiation doses which can be achieved while working with, e.g., radioactive samples. The three major principles to assist with maintaining doses “As Low As Reasonably Achievable” are time, distance, and shielding.

In the first part of the experiment the interrelation of activity, energy dose, and energy-dose rate, as well as their dependence on time and distance, are studied for some $\gamma$-ray sources, using a Geiger-Müller counter. The effect of shielding on the radiation dose is subject of the second part of the experiment. Attenuation coefficients of $\gamma$ radiation in different materials are determined. Fundamentals on generation and decay of activated samples are treated in the third part of the experiment. Therefore, the decay curve of an excited energy state in the nuclide $^{116m}_1\text{In}$, which has been activated by (n,$\gamma$) reactions, is measured.
1 Dosimetry

1.1 Introduction and basic definitions

The Activity of a probe is its number of radioactive decays per seconds. Its unit is Becquerel (Bq)–[s⁻¹] (formerly: 1 Curie [Ci] = $3.7 \times 10^{10}$ Bq).

The dose is a measure of the energy absorption in matter due to irradiation. The unit of the energy dose is 1 Gray [Gy] = $1 \frac{J}{kg}$ (formerly: 1 rad [rd] = $0.01 \frac{J}{kg}$).

As a direct measure of the energy dose is very difficult (why?), usually the ionization dose is measured in units of $\frac{C}{kg}$ (formerly: 1 Roentgen [r] = $2.58 \times 10^{-4} \frac{C}{kg}$). This corresponds to an energy dose of 0.01 rd in air and water, as the average energy needed for ionization is 33 eV).

The biological impact of the different kinds of radioactive radiations on matter differ considerably (why?). To calculate the equivalent dose, the energy dose is multiplied with a quality factor QF dependent on radiation between 1 (for X-ray radiation and $\gamma$ rays) and 10-20 ($\alpha$ particles, heavy recoil nuclei). The unit for the equivalent dose is the Sievert [Sv] = energy dose [Gy] $\cdot$ QF (formerly: 1 Roentgen equivalent man [rem] = 1 rd $\cdot$ QF = 0.01 Sv).

In addition the effective equivalent dose considers the irradiation sensitivity of the different organs of a body. The different types of a body are weighted, with 1 the sum over the total body. The gonads (0.25), the lung, the red marrow and neural tissue (0.12) are very sensitive to irradiation, while muscle tissue and the skin (0.03) are less sensitive.

Keywords/questions:

- The dose, its definition and measurement
1.1 Introduction and basic definitions

- $(\alpha, \beta, \gamma)$ radiation and its impact on matter
- Origin of natural radioactivity, decay schemes, radioactive series
- The ALARA radiation safety principle and its implementation
- Technique of the Geiger-Müller counter

1.1.1 The dose rate

The energy flow of $\gamma$ rays is defined as

$$I = \frac{dE}{dF} = E_\gamma \cdot \phi \quad \left[ \frac{\text{MeV}}{\text{cm}^2 \cdot \text{s}} \right]$$

and decreases in matter with the range $dx$ as:

$$\frac{d}{dx}(E_\gamma \cdot \phi) = \frac{dI}{dx} = I \cdot \mu_a = E_\gamma \cdot \phi \cdot \mu_a \quad \left[ \frac{\text{MeV}}{\text{cm}^3 \cdot \text{s}} \right].$$

With:

- $E_\gamma$ the photon energy $h\nu$ in MeV
- $\phi$ the flow in cm$^{-2}$ s$^{-1}$
- $\mu_a$ the linear absorption coefficient in cm$^{-1}$
- $\rho$ the density in g cm$^{-3}$
- $\mu_a/\rho$ the mass absorption coefficient in cm$^2$ g$^{-1}$

The energy absorption of matter with mass $dm$ per time units gives the energy-dose rate $\dot{D}$ [MeV g$^{-1}$ s$^{-1}$]. Therefore:

$$\dot{D} = \frac{d\dot{E}}{dm} = \frac{1}{\rho} \cdot \frac{dI}{dx} = I \cdot \frac{\mu_a}{\rho} = E_\gamma \cdot \phi \cdot \frac{\mu_a}{\rho} \quad \left[ \frac{\text{MeV}}{\text{g} \cdot \text{s}} \right].$$

If the excited nucleus decays by more than one $\gamma$ ray, the emission of all $\gamma$ rays has to be considered:

$$\dot{D} = \phi \cdot \sum_{i=1}^{n} \alpha_i \cdot E_\gamma \cdot \frac{\mu_a}{\rho} \quad \text{with } \alpha_i = \text{fraction of the corresponding } \gamma \text{ radiation.}$$

For distances, which are large compared to the dimension of a probe, the dose rate decreases with the square of the distance (why?). Furthermore, the dose rate $\dot{D}$ is proportional with the probe activity $A$ as:

$$\dot{D} = D_0 \cdot \frac{A}{x^2}$$

with $D_0$ the dose constant of a nucleus, which is given in units of $[\frac{1 \text{ m}^2}{\text{kg}}]$ (for air).
1.2 Measurements and tasks

1.2.1 Dose rate and dose constant

For the lab report, the following has to be considered:

1. Convert the dose rate in a way, that $E_{\gamma}$ can be inserted in units of [MeV], $\phi$ in [cm$^{-2}$ s$^{-1}$] and $\frac{\mu_{a}}{\rho}$ in [cm$^{2}$ g$^{-1}$], to obtain $\dot{D}$ in [W kg$^{-1}$].

2. Give also a formula for the dose constant $D_0$ in [J m$^{2}$ kg$^{-1}$], where $E_{\gamma}$ and $\frac{\mu_{a}}{\rho}$ can be inserted in units of [MeV] and [cm$^{2}$ g$^{-1}$].

3. What is the relation between the cross section $\sigma$ for absorption, the linear absorption coefficient $\mu_{a}$, and the mass absorption coefficient $\frac{\mu_{a}}{\rho}$?

4. Describe the difference between absorption coefficient and attenuation coefficient. Why is the ratio of both coefficients energy dependent?

5. Calculate the dose constants $D_0$ for $\gamma$ rays of the $^{137}$Cs, $^{60}$Co, and $^{22}$Na sources, respectively. Use the equation derived for $D_0$ and the level schemes given in the appendix. Also use $\frac{\mu_{a}}{\rho} = 0.028$ cm$^{2}$ g$^{-1}$.

1.2.2 Dose rate measurements

The dose rate is directly proportional to the count rate of a Geiger-Müller counter. In following experiments, the dose rate is measured using $\gamma$-ray sources. How large is the $\gamma$-ray detection efficiency of a Geiger-Müller counter?

1. The count rate includes events from background radiation. For correction, the background rate has to be measured for 30 min (the sources have to be shielded!). What are the sources of this background radiation?

2. To determine the effective zero point $x_0$ of the distance scale, measure for 10 reasonable(!) distances $x - x_0'$ the count rate $\dot{N}$ of the strongest $^{137}$Cs calibration source. Each measurement should last about 60 s. $x_0'$ is initially an arbitrary position of the zero point.

3. Plot $\dot{N}^{-\frac{1}{2}}$ versus $x$.

4. Give the total error of the data points. How do you account for background correction?

5. Fit the data points, using the linear function $f(x) = y_0 + a \cdot x$, and determine $x_0$ and give the errors of the fit.

6. Compare the calculated dose rate at the distance $x - x_0$ with the measured count rate and determine the calibration factor $\epsilon = \frac{\dot{D}}{\dot{N}}$ of the counter in [W s kg$^{-1}$]. What is the error of the calibration factor? Keep in mind that the activity of the sources, stated in Table A.1, are not the activity at the day of the experiment!
1.2.3 Activity measurements

1. Repeat tasks no. 2 to 4 given in section 1.2.2. for each of the three other γ-ray sources, to determine their activity.

2. Why is $x_0$ not at the same position for the different γ-ray sources? Explain the relation between $x_0$ and the γ-ray energy qualitatively.

3. Calculate the activity of the three sources, using the fit parameter $a$, the dose constant $D_0$ and the calibration factor $\epsilon$, obtained in section 1.2.2. Assume $\frac{\mu a}{\rho} = 0.028 \, \text{cm}^2 / \text{g}$. Compare your results to the values given in Table A.1. Again, keep in mind that the activity of the sources, stated in Table A.1, are not the activity at the day of the experiment!

4. Calculate the sum of γ-ray dose rates for all investigated radioactive sources and determine the time needed to obtain a dose of 1.5 mSv (max. dose per year for people occupationally exposed to radiation) at a distance of 1 meter. Why is your body not fully exposed to the calculated dose? Compare the result with the natural radiation exposition! Calculate also the dose rate of the measured background radiation and compare it with literature values. What strikes you?

2 Attenuation of γ radiation

2.1 Introduction

Following the interaction of γ rays with matter, the attenuation of γ radiation is described by the Beer-Lambert law. If an absorber with thickness $d$ and area $A$ is placed between a γ-ray source and a detector, the intensity of the radiation at the position of the detector is given by

$$I(d) = I_0 \cdot e^{-\mu d}, \quad \text{with } I_0 = I(d = 0)$$

$\mu$ is the linear attenuation coefficient. It describes the probability of an interaction (per path length) of a γ quantum with the absorber material:

$$\mu_{\text{ges}} = \mu_{\text{photoeffect}} + \mu_{\text{Compton scattering}} + \mu_{\text{pair production}}$$

The Beer-Lambert law can also be written in terms of the interaction cross section $\sigma$ of γ radiation with matter (Why?):

$$I(d) = I_0 \cdot e^{-n\sigma}, \quad \text{with } n = \frac{N_A \cdot N_{\text{mol}}}{A}$$

Keywords/questions:

- Interaction of γ radiation with matter: photoeffect, Compton scattering, pair production
- Beer-Lambert law
- linear attenuation coefficient, interaction cross section
2.2 Measurements and tasks
The linear attenuation coefficients $\mu$ of Al and Pb for 662-keV $\gamma$ rays of a $^{137}$Cs source have to be measured. Therefore, absorber sheets of both materials are available with different thicknesses. Use for this measurement the strongest $^{137}$Cs source and place the source at a fixed position about 10 cm away from the Geiger-Müller counter.

1. Install the dedicated holding structure for the absorber sheets between the $^{137}$Cs source and the Geiger-Müller counter. Then start a measurement WITHOUT absorbers in order to receive the initial $\gamma$-ray intensity $I_0$. The measurement should last about 60 s.

2. Put the aluminum or lead sheets into the holding structure directly in front of the counter. Measure the remaining $\gamma$-ray intensity $I(d)$ for at least six different total thicknesses $d$ of the absorber. Again, each measurement should last for at least 60 s.

3. Plot the measured intensities in an appropriate way as a function of the thickness of the absorbers and deduce the linear attenuation coefficient $\mu$ of aluminum and lead, respectively, at a $\gamma$-ray energy of 662 keV. Remember to correct for the background rate. Compare your results to literature values.

4. Calculate the atomic interaction cross sections $\sigma$ (in barn) for $\gamma$ radiation, using your deduced linear attenuation coefficients $\mu$ in combination with densities and molar masses.

5. Deduce the (effective) dependency of the absorption cross section $\sigma$ on the atomic number $Z$ and discuss your results.

3 Neutron activation and lifetime measurement

3.1 Introduction
For this part of the experiment, a radioactive sample is prepared by neutron activation, following the reaction $^{115}$In$(n,\gamma)^{116}$In. The neutron source consists of two Am-Be sources, in which the $^{241}$Am isotope decays by the emission of an $\alpha$ particle. During the further process the $\alpha$ particle can react with the beryllium: $^9$Be$(\alpha,n)^{12}$C (Why?).

A thick Paraffin coating encloses both neutron sources for neutron moderation. In a distance of approximately 5 cm, the $^{115}$In sample needs about 6 hours of neutron activation to obtain radioactive equilibrium. Activation of the In probe, its extraction and transport to the experimental area is operated by the supervising tutor.

Keywords/questions:

- Neutron sources, neutron activation
- Reaction cross section
3.2 Measurements and tasks

The time-dependent activity of the In sample has to be measured during a time period of 1.5 hours. Therefore, the count rate has to be measured for 250 s every 5 minutes. Consider also the transportation time needed to put the sample from the neutron source to the measurement place (beginning of the measurement).
Plot the count rate on a semi-logarithmic scale as a function of time and determine the lifetime, using a linear fit. Use the level scheme to calculate the $\gamma$-ray dose constant of $^{116}\text{m}_1\text{In}$ and the calibration factor to determine the activity of the sample. Moreover, determine the number of produced $^{116}\text{In}$ nuclei ($N(t = 0)$). Assuming, that only thermal neutrons were captured and that after 6 hours an equilibrium between production and decay of the radioactive nuclei is given, the neutron flux of the neutron sources can be calculated at the activation position (mass of the $^{\text{nat}}\text{In}$ samples: 1.9465 g (#1), 2.2082 g (#2); purity 99.99%). The thermal neutron capture cross section $\sigma_c = 160 \text{ b}$ for $^{115}\text{In}$. Compare it with the theoretical value (activity of the Am-Be sources: 10.2 MBq (#1), 68.8 MBq (#2); neutron yield: $7.3 \times 10^{-5} \frac{\text{neutrons}}{\text{Bq} \cdot \text{s}}$; distance of the In sample to the Am-Be sources: approx. 5 cm).
A Appendix

A.1 $\gamma$-ray source properties

<table>
<thead>
<tr>
<th>source</th>
<th>half-life</th>
<th>$\gamma$-ray energy [keV]</th>
<th>branching ratio</th>
<th>activity</th>
<th>date</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{22}\text{Na}$ (AJ-2420)</td>
<td>2.6019 years</td>
<td>511 1274.537</td>
<td>181 99.935</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$^{60}\text{Co}$ (Stab 15)</td>
<td>5.2714 years</td>
<td>1173.228 1332.490</td>
<td>99.857 99.983</td>
<td>7.65 kBq</td>
<td>15.05.2013</td>
</tr>
<tr>
<td>$^{137}\text{Cs}$ (Stab 9)</td>
<td>30.07 years</td>
<td>661.657</td>
<td>85.1</td>
<td>302 kBq</td>
<td>15.05.2013</td>
</tr>
<tr>
<td>$^{137}\text{Cs}$ (7091)</td>
<td>30.07 years</td>
<td>661.657</td>
<td>85.1</td>
<td>73.5 kBq</td>
<td>15.05.2013</td>
</tr>
</tbody>
</table>

A.2 Decay schemes

- $^{60}\text{Co}$ (5+ $\beta^-$, Q: 2.824 MeV)
- $^{137}\text{Cs}$ (7/2+ $\beta^-$, Q: 1.176 MeV)
A.2 Decay schemes

\[ \text{Ne}^{22}_{2+} \rightarrow \beta^+ (90\%), \text{EC (9.9\%)} \]

\( Q_{\text{EC}} : 2.842 \text{ MeV} \)

\[ \text{Na}^{22}_{3+} \rightarrow \beta^+ (90\%), \text{EC (9.9\%)} \]

\[ \text{In}^{116}_{0+} \rightarrow \beta^- (8.7\%), 3.275 \text{ MeV} \]

\[ \text{Sn}^{116}_{0+} \rightarrow \beta^- (98.7\%), 1.2936 \text{ MeV} \]

\[ \text{Sn}^{116}_{2+} \rightarrow \beta^- (0.8\%), 1.7569 \text{ MeV} \]

\[ \text{Sn}^{116}_{4+} \rightarrow \beta^- (0.26\%), 2.1123 \text{ MeV} \]

\[ \text{Sn}^{116}_{5+} \rightarrow \beta^- (10.2\%), 2.3909 \text{ MeV} \]

\[ \text{Sn}^{116}_{2+} \rightarrow \beta^- (33.8\%), 2.5292 \text{ MeV} \]

\[ \text{Sn}^{116}_{4+} \rightarrow \beta^- (52.1\%), 3.0464 \text{ MeV} \]

\[ \text{Sn}^{116}_{0+} \rightarrow \beta^- (2.71\%), 0 \text{ MeV} \]
Operating instructions for electric powered equipment in the rooms for the practical course

Danger for people
Burns or death by high electric currents

Safety measures:
Pay attention that cables and plugs are not damaged and use them only in the way they are designed for.
In case of damage, or if you have the suspicion that they are damaged inform immediately your supervisor, do not try to repair anything yourself.
Use at maximum one extension cord and only for low powered equipment.
For equipment with large power consumption only wall outlets should be used.

In case of emergency:
Pull the mains plug.
In case of fire: Switch of all electrical equipment as far as possible.

First aid:
People who can give first aid are Görgen, Rolke, Rudolph, Thiel
In case of shock call immediately an emergency physician Tel. 01-112 (from any telephone in the institute, or mobile 112)
Hospital for accidents: evangelisches Krankenhaus Weyertal.
In case of all accidents also the managing director of the institute has to be informed.
In case of a working inability of 3 or more days an accident report form available from the secretary has to be filled.
The first aid box can be found in the inner stairwell.

13/11/2014
Blazhev
Operating instructions for high voltage equipment in the rooms for the practical course

Danger for people
Instantaneous death by ventricular fibrillation

Safety measures:
Pay attention that cables and plugs are not damaged and use them only in the way they are designed for.
In case of damage, or if you have the suspicion that they are damaged inform immediately your supervisor, do not try to repair anything yourself.
Switch on the high tension only after the cables have been connected and switch it off before disconnecting.

In case of emergency:
Switch off the high tension
In case of fire: Switch off all electrical equipment as far as possible

First aid:
People who can give first aid are Görgen, Rolke, Rudolph, Thiel
In case of shock call immediately an emergency physician Tel. 01-112 (from any telephone in the institute, or mobile 112)
Hospital for accidents: evangelisches Krankenhaus Weyertal.
In case of all accidents also the managing director of the institute has to be informed.
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13/11/2014
Blazhev
**B OPERATING INSTRUCTIONS**

for the rooms of the practical course / institute for nuclear physics

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### Identification of Substance

**Lead bricks**

Lead bricks packed in plastic foil can be touched without precautions. They are very heavy, **put them only in places where they can not drop on your feet!** If the foil is damaged please pay attention to the following instructions:

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### Danger for People and Environment

- May cause harm to the unborn child.
- May cause damage to organs through prolonged or repeated exposure.
- Very toxic to aquatic life with long lasting effects

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### Safety Measures and Rules

**Do not touch any lead brick with a damaged protective foil. If the foil is damaged or if you suspect that it is damaged please inform immediately your supervisor**

**Breathing equipment:** In case of fire toxic metal oxide smoke can be released. Wear self contained breathing apparatus.

**Protective equipment:** If the protective foil is damaged, lead brick must be touched only with protective gloves.

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### In Case of Accident

Fire brigade 01-112 from any phone, mobil 112

Leave the contaminated area and inform your supervisor. If lead dust has to be removed wear always safety glasses, protective gloves and in case of large quantities a breathing apparatus. Fire extinguishing measures have to be taken according to the surrounding materials. In case of a fire dangerous fumes are generated. Please take actions according to the emergency action plan. Call the fire brigade. Lead must not get in the sewage system.

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### First Aid

**emergency physician 01-112, mobil 112**

After eye contact: Rinse opened eye for several minutes under running water. Then consult doctor.

After skin contact: Instantly wash with water and soap and rinse thoroughly.

After swallowing: Seek immediate medical advice.

After inhalation: Supply fresh air. If required provide artificial respiration. Keep patient warm. Consult doctor if symptoms persist.

First aid can provide: Göggen, Rolke, Rudolph, Thiel

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### Disposal

Do not put lead in the sewage or the dust bin. Disposal has to be made via Dr. Blazhev or Bereich 02.2
Radiation protection directive
for the handling of radioactive sources in the practical courses
of the Institute of Nuclear Physics of the University of Cologne.

Issued 13/11/2014

1. Admission restrictions
Persons under the age of 18 years are not allowed to work in the practical course.
Pregnant women must not work with radioactive sources or in rooms in which radioactive
sources are located.
Only students who have filled the registrations sheet and participated in the radiation
protection instructions are allowed to carry out experiments with radioactive sources in the
rooms of the practical course under the instruction of a supervisor. Visitors must not enter the
rooms of the practical course when radioactive sources are located there.

2. Handling of radioactive sources
The radioactive sources are put in the experimental setup or in the lead shielding nearby by a
radiation protection officer or an instructed person before the beginning of the practical
course. These people document the issue in the list which is placed in the storage room (see
appendix B). If radioactive sources have to be transported to other Physics institutes of the
University of Cologne a list according to appendix A has to be attached to the transporting
container.

When the practical course is finished the same people bring the radioactive sources back to
the storage room.

A sign „Überwachungsbereich, Zutritt für Unbefugte verboten“ which means „monitored in-
plant area, admission only for authorized personnel“ has to be attached to the door of a room
of the practical course when radioactive sources are inside.

It is not allowed to remove radioactive sources from the rooms of the practical course without
contacting the radiation protection officer before.

During the practical course the radioactive sources must only be located at the place necessary
for the measurements or behind the lead shielding nearby the experimental setup.

If you leave the rooms of the practical course make certain that doors are locked and windows
are closed, even if you only leave for a short time.

Alpha-Sources are built in the experimental setup and students are not allowed to take them
out.

Beta-Sources must only be handled by protective gloves or tweezers.
3. What to do in case of emergency

Any damages or suspected damages of radioactive sources must immediately be reported to the supervisor or the radiation protection officer. It is not allowed to continue work with such a source. Contaminated areas should be cordoned off immediately.

In case of fire, explosion or other catastrophic events besides the managing director and the janitor a radiation protection officer must be called in.

4. Radiation protection officers

Radiation protection officers for radioactive sources in the Institute for Nuclear Physics of the University of Cologne are:

<table>
<thead>
<tr>
<th>Name</th>
<th>Heinze</th>
<th>Fransen</th>
<th>Dewald</th>
</tr>
</thead>
<tbody>
<tr>
<td>Responsibility</td>
<td>Practical course</td>
<td>Experimental halls, work with radioactive sources, except of the practical course</td>
<td>Work in other institutes, Transport of radioactive sources, accelerator</td>
</tr>
</tbody>
</table>
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