Institute for Nuclear Physics
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Practical Course Master

M3.1: Dosimetry

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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 γ-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 γ 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}In, which has been activated by (n,γ) 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]=[$\frac{1}{\mathrm{s}}$] (formerly: 1 Curie [Ci] = 3.7×10^{10} Bq).

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

As a direct measure of the energy dose is very difficult (why?), usually the **ionization dose** is measured in units of $\frac{\mathrm{C}}{\mathrm{kg}}$ (formerly: 1 Roentgen [r] = 2.58×10^{-4} $\frac{\mathrm{C}}{\mathrm{kg}}$). 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 γ-rays) and 10-20 (α particles, heavy recoil nuclei). The unit for the equivalent dose is the Sievert [Sv] = energy dose [Gy] · QF (formerly: 1 Roentgen equivalent man [rem] = 1 rd · 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
- (α, β, γ) 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 γ-rays is defined as

$$I = \frac{d\dot{E}}{dF} = E_\gamma \cdot \phi \quad \left[\frac{\mathrm{MeV}}{\mathrm{cm}^2\,\mathrm{s}}\right]$$

and decreases in matter with the range dx as:

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

With:

E_γ	the photon energy $h\nu$	in MeV
ϕ	the flow	in $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
μ_a	the linear absorption coefficient	in cm^{-1}
ρ	the density	in $\mathrm{g\,cm}^{-3}$
$\frac{\mu_a}{\rho}$	the mass absorption coefficient	in $\mathrm{cm}^2\,\mathrm{g}^{-1}$

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

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

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

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

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 $\left[\frac{\mathrm{J\,m}^2}{\mathrm{kg}}\right]$ (for air).

1.2. Measurements and tasks

1.2.1. Dose rate and dose constant

For the lab report, the following must be considered:

1. Convert the dose rate in a way, that E_γ can be inserted in units of [MeV], ϕ in $[\mathrm{cm}^{-2}\,\mathrm{s}^{-1}]$ and $\frac{\mu_a}{\rho}$ in $[\mathrm{cm}^2\,\mathrm{g}^{-1}]$, to obtain $\dot{D}$ in $[\mathrm{W\,kg}^{-1}]$.
2. Give also a formula for the dose constant D_0 in $[\mathrm{J\,m}^2\,\mathrm{kg}^{-1}]$, where E_γ and $\frac{\mu_a}{\rho}$ can be inserted in units of [MeV] and $[\mathrm{cm}^2\,\mathrm{g}^{-1}]$.
3. What is the relation between the cross section σ for absorption, the linear absorption coefficient μ_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 γ-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 $\frac{\mu}{\rho} = 0.028\ \frac{\mathrm{cm}^2}{\mathrm{g}}$.

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 γ-ray sources. How large is the γ-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 must 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 $[\mathrm{W\,s\,kg^{-1}}]$. 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 ϵ, obtained in section 1.2.2. Assume $\frac{\mu_a}{\rho} = 0.028\ \frac{\mathrm{cm}^2}{\mathrm{g}}$. 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! Also Calculate 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

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

μ 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 σ 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 μ of Al and Pb for 662-keV γ-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 of 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 γ-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 γ-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 μ of aluminum and lead, respectively, at a γ-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 σ (in barn) for γ radiation, using your deduced linear attenuation coefficients μ in combination with densities and molar masses.
5. Deduce the (effective) dependency of the absorption cross section σ 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,γ)^{116}In. The neutron source consists of two Am-Be sources, in which the ^{241}Am isotope decays by the emission of an α particle. During the further process the α particle can react with the beryllium: ^{9}Be(α,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

- Radioactive decay
- Lifetimes of excited nuclear states, nuclear isomeric states
- Lifetime measurement

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).

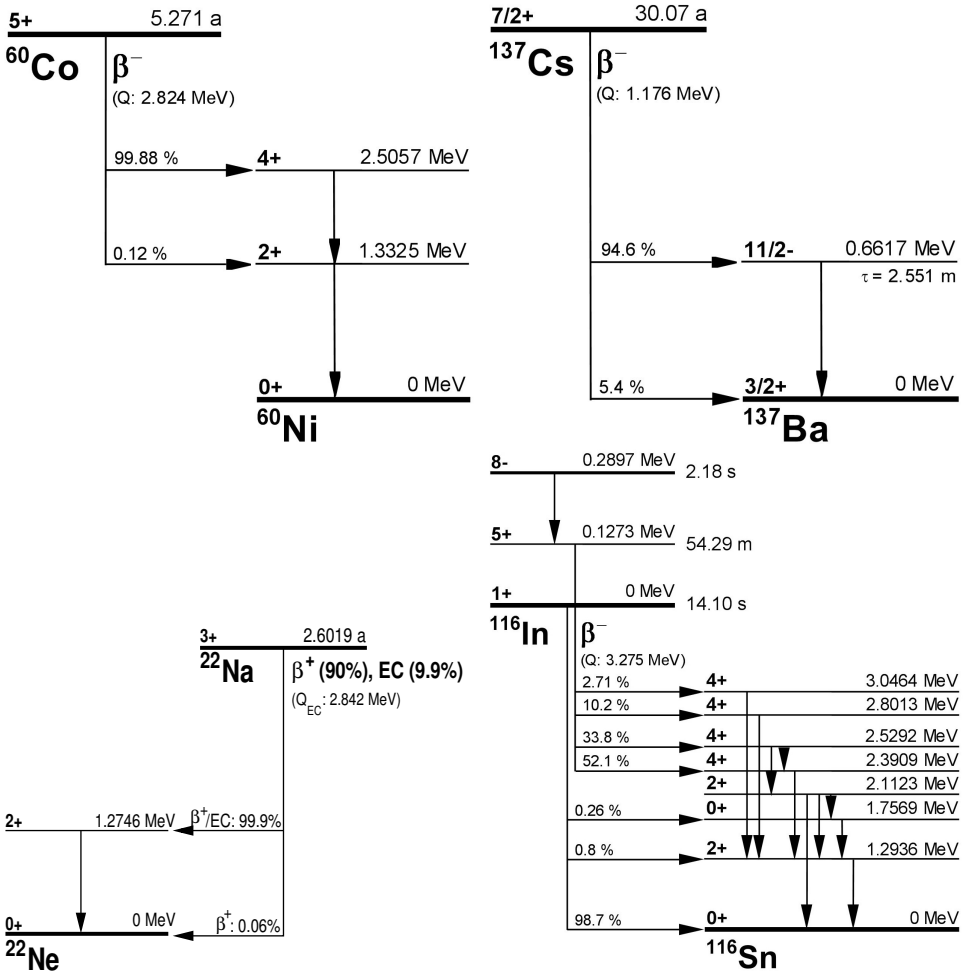
Plot the count rate on a semi-logarithmic scale as a function of time and determine the lifetime, using a linear fit. Use the level scheme to calculate the γ-ray dose constant of ^{116m_1}In and the calibration factor to determine the activity of the sample. Moreover, determine the number of produced ^{116}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 $^{\text{nat}}$In samples: 1.9465 g (#1), 2.2082 g (#2); purity 99.99%). The thermal neutron capture cross section $\sigma_c = 160$ b for ^{115}In. Compare it with the theoretical value (activity of the Am-Be sources: 10.2 MBq (#1), 68.8 MBq (#2); neutron yield: 7.3×10^{-5} $\frac{\text{neutrons}}{\text{Bq·s}}$; distance of the In sample to the Am-Be sources: approx. 5 cm).

A. Appendix

A.1. γ-ray source properties

Isotope	Source	Half-life [a]	γ-ray energy [keV]	Branching [%]	Activity [kBq]	Date
^{22}Na	AJ-2420	2.6019	511	181		
			1274.537	99.935		
^{60}Co	Stab 15	5.2714	1173.228	99.857	7.65	15.05.2013
			1332.490	99.983		
^{137}Cs	Stab 9	30.07	661.657	85.1	302	15.05.2013
^{137}Cs	7091	30.07	661.657	85.1	73.5	15.05.2013

A.2. Decay schemes



References

[1] Bethge, K.:
Kernphysik
Springer Verlag (1996).

[2] Bevington, P. R.:
Data Reduction and Error Analysis for the Physical Sciences
McGraw-Hill (2001).

[3] Evans, R. D.:
The Atomic Nucleus
McGraw-Hill (1955).

[4] Hänsel, H.; Neumann, W.:
Physik – Atome, Atomkerne, Elementarteilchen
Spektrum (1995).

[5] Kreyszig, E.:
Statistische Methoden und ihre Anwendung
Vandenhoeck & Rupprecht (1979).

[6] Schultz, H. G.; Vogt, H.:
Physikalische Grundlagen für Dosimetrie und Strahlenschutz
Hanser Fachbuchverlag (2007).

[7] Siegbahn, K. M.:
Alpha-, Beta- and Gamma-Ray Spectroscopy
Elsevier Science Ltd. (1965).

[8] Zurmühl, R.:
Praktische Mathematik
Springer (1965).