Dosimetry in Medical Physics

Advanced Lab Course Experiment at the Department of Medical Physics

November 20, 2017

1. Introduction

Dosimetry is an essential component of any workflow related to radioactivity. Two basic methods of dosimetry, often employed in Medical Physics, will be presented and used in this lab course.

The first method is film based dosimetry by means of radio-chromic films. The second method consists of measurements with a scintillation detector in a water phantom. Furthermore, a Monte-Carlo simulation tool will be used to predict dose distribution into the water phantom and measured by the scintillation detector.

Throughout the experiments a Strontium-90 (^{90}Sr)radiation source will be used. Such beta-emitting ^{90}Sr sources are usually employed in brachytherapy (from greek "close"), to treat certain types of cancer. Example applications of brachytherapy are cervical, breast and prostate cancers.

2. Personal Safety When Working With Radioactive Materials

For your own safety, please adhere to the three cardinal rules of radiation protection:

1. **Time** - As short as possible
2. **Distance** - As far away as possible
3. **Shielding** - As thick as necessary

Should any questions arise don't hesitate to contact your supervisor.

In case of emergency call the **TUM fire-department** under **112** (from the phone in room 143) or **089 289 112 (from your mobile)** and inform Dr. Thirolf in room 114, phone 14064.

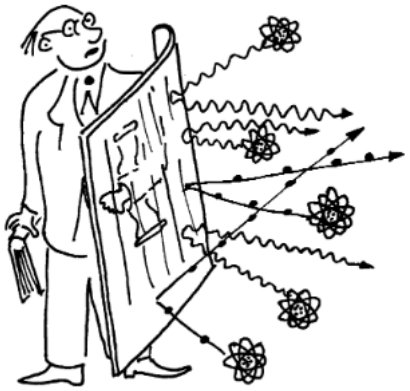


Figure 2.1.: Shield yourself

3. Physical Background

This chapter contains a summary of the basic concepts of radioactivity of interest to this lab course. In-depth presentation of the different types of ionizing radiation can be found in chapters 1 and 2 of [1] "Nuclear medicine physics: a handbook for teachers and students"[1]. A detailed dosimetry textbook (written in German) is [4], which is also available here.[2]

3.1. Radioactive Decay - Physical Quantities and Laws

Unstable nuclei undergo radioactive decay in order to transit to a lower energy state. There are several known paths of decay that alter the proton to neutron ratio of the nucleus in question. As a result, one or more particles are emitted, depending on the type of decay.

Another way for an excited nucleus to release excess energy is emitting photons. If these originate from the nucleus, they are called gamma rays (γ). Should they originate from atomic transitions (transitions of orbital electrons), they are called x-rays.

3.1.1. Relevant Formulas and SI-Units

3.1.1.1. Activity

The measurable quantity of nuclear decays is the *activity* A. It is defined as the "the average number of radioactive decays dN per time-interval dt":

$$A = \left\langle \frac{dN}{dt} \right\rangle ,$$

with the SI unit of activity being *Becquerel*, interpreted as one nuclear decay per second and expressed in dimensions of inverse second: $[A] = 1\,Bq = \frac{1}{s}$.

3.1.1.2. Law of Radioactive Decay

Since it is not possible to predict the exact moment when a specific nucleus will decay, one is restricted to describing the statistical behavior of an ensemble of unstable nuclei. Defining the *decay constant* λ as "the probability of the decay of a single radioactive nucleus per time unit" yields the *law of radioactive decay* in differential form:

[1] available at `http://www-pub.iaea.org/books/IAEABooks/10368/Nuclear-Medicine-Physics`

[2] `https://login.emedien.ub.uni-muenchen.de/login?url=http://dx.doi.org/10.1007/978-3-8348-2238-3`

$$-\frac{dN}{N} = \lambda dt, \tag{3.1}$$

where N is the number of unstable nuclei present at time t and dN the number of unstable nuclei that will decay in the infinitesimal time interval dt. The dimension of the decay constant is $[\lambda] = \frac{1}{s}$.

The solution of the differential equation 3.1 is

$$N(t) = N_0 e^{-\lambda t}. \tag{3.2}$$

with N_0 denoting the initial number of radioactive nuclei at time 0 and N_t the number of remaining radioactive nuclei after time t, assuming a decay constant λ.

This formula can be expressed in terms of activity A by using the relation $A = \lambda N$:

$$A(t) = A_0 e^{-\lambda t}. \tag{3.3}$$

3.1.1.3. Half-Life

An often used quantity characterizing specific radioactive isotopes is their *half-life* $T_{\frac{1}{2}}$. Considering an initial amount of isotopes N_0 in the law of radioactive decay, on average, there will be $\frac{N_0}{2}$ unstable nuclei left when $T_{\frac{1}{2}}$ has passed:

$$T_{\frac{1}{2}} = \frac{ln2}{\lambda}. \tag{3.4}$$

3.1.1.4. Mean Lifetime

By inverting the decay constant, one obtains the *mean lifetime* τ. It denotes the average time passing before an instable nucleus will decay:

$$\tau = \frac{1}{\lambda} = \frac{T_{\frac{1}{2}}}{ln\,2}. \tag{3.5}$$

3.1.1.5. Chain of Decays

Should the product of a radioactive decay be radioactive itself, then the whole process is known as a *decay chain*: isotope A decays into isotope B, increasing the number of B atoms present. These in turn produce isotope C while reducing the number of B.

The differential equation can be written as

$$\frac{dN_B}{dt} = -\lambda_B N_B + \lambda_A N_A(t_0) e^{-\lambda_A t}. \tag{3.6}$$

Solving this, we obtain

$$N_B = N_A(t_0)\frac{\lambda_A}{\lambda_B - \lambda_A}(e^{-\lambda_A t} - e^{-\lambda_B t}). \tag{3.7}$$

3.1.2. Radioactive Decay Processes

Nuclear Transmutations

What is defined as nuclear transmutations is the change in the composition of a nucleus. Thus the term is used to describe radioactive processes converting one element or isotope into another. There are several experimentally observed types of radioactive transmutation. In the following subsections, the main transmutation type of interest for this laboratory course is the beta decay. Nevertheless, a brief description of other nuclear transmutation types will be briefly mentioned.

3.1.2.1. Energetic Considerations

A quantity of high importance to all kinds of nuclear decays is the energy released by a radioactive decay, called *decay energy* Q. It is often given in units of *electron volts* and is calculated by

$$Q = [(m(a_1) + \ldots + m(a_n)) - (m(b_1) + \ldots + m(b_m)] * c^2.$$

It expresses the rest mass difference between the parent (particles a_x) and daughter (particles b_x) atom. All natural (not induced) radioactive decay has a positive Q-value.

3.1.2.2. Alpha Decay

When a parent nucleus undergoes *Alpha Decay* a Helium nucleus called *alpha particle* (symbol α) is emitted.

$$\alpha = {}^4_2 He^{2+}. \tag{3.8}$$

The daughter nucleus has an atomic number and mass number are reduced by two and four respectively. The difference in binding energy before and after the decay is split between the products while maintaining conservation of momentum.

$${}^A_Z X_N \Longrightarrow {}^{A-4}_{Z-2} Y_{N-2} + \alpha + Q. \tag{3.9}$$

The released energy is virtually completely transfered to the alpha particle due to $m_N(Y) \gg m(\alpha)$, making the energy spectra of them discrete. Although experimental data shows some smearing of this discrete value, as the daughter nuclei do in practice gain some recoil momentum.

Natural alpha decay appears in nearly all elements with $Z \geq 82$. Below that border only induced alpha decays can occur, by providing enough energy, for example via photodisintegration (laser, high energy gamma- or x-rays) as well as bombardment with neutrons. A well known technical application is the use of thermal neutrons in nuclear fission reactors.

3.1.2.3. Beta Decay

The radioactive source of this lab course (^{90}Sr) decays via electron emission (beta decay) to Yttrium (^{90}Y), which in its turn decays again via beta decay, with a decay rate of 99.9885%.

This kind of decay is caused by a surplus of neutrons in an unstable nucleus. Such a neutron can transform into a proton, a electron and an electron antineutrino:

$$n \Rightarrow p + e^- + \overline{\nu_e} + Q, \tag{3.10}$$

where Q is the energy released by this process. While the proton remains in the daughter nucleus, the electron and the antineutrino are emitted.

Considering the decay on an atomic scale shows that when the parent nucleus ${}^A_Z X_N$ decays, a daughter nucleus ${}^A_{Z+1} Y_{N-1}$ is produced:

$${}^A_Z X_N \Longrightarrow {}^A_{Z+1} Y_{N-1} + e^- + \overline{\nu_e} + Q. \tag{3.11}$$

Due to the kinetic energy being shared between the electron and the neutrino, the energy of the spectrum of the emitted electron is not discrete. Instead, it follows a distribution as shown in figure 3.1.

The average energy of the emitted electrons amounts to approximately $\langle E \rangle \approx \frac{1}{3} E_{max}$.

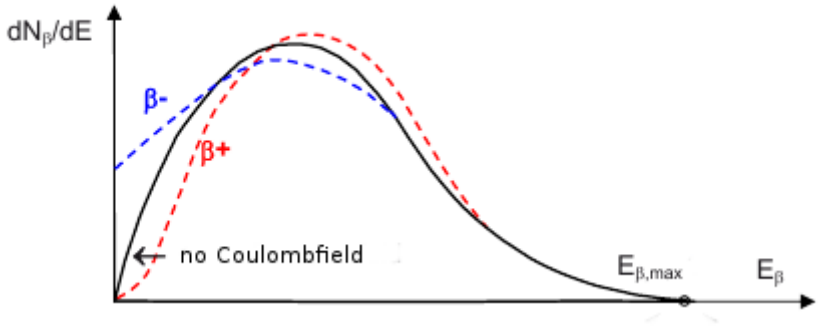


Figure 3.1.: Electron spectrum from beta decays. Blue-Dashed: Electrons with Coulomb Correction. Red-Dashed: Positrons with Coulomb Correction. Black: Without Coulomb Correction
[4]

A *positive beta decay* (positron emission) is possible as well. Instead of surplus neutrons the nucleus carries an excessive amount of protons. This leads to the conversion of a proton into a neutron while emitting both a positron and an electron neutrino:

$${}^A_Z X_N \Longrightarrow {}^A_{Z-1} Y_{N+1} + e^+ + \nu_e + Q. \tag{3.12}$$

Regarding the energy spectra of both positive and negative beta decay one needs to be aware of the Coulomb Field of the nucleus produced after the decay. Repulsion or attraction respectively leads to differences in the spectra for both types of emitted electrons or positrons, see figure 3.1 on the previous page.

Radioactive Processes Without Transmutations

3.1.2.4. Gamma Decay

Gamma Decay is a mechanism for the deexcitations of a nucleus via the emission of a photon. The photon will carry the energy difference between the initial and final nucleus excitation state.

There is also the possibility to transfer that nuclear deexcitation energy to an orbital electron of the atom. This process is called *Internal Conversion*. Electrons ejected this way carry a kinetic energy that is the transition energy of the nucleus reduced by their binding energy B :

$$E_{e,kin} = \triangle E - B.$$

The orbital gap created can subsequently be filled by an electron from the outer shells, where the binding energy is lower. As long as there are electrons left in shells bound with less energy than at the position of the hole, further atomic transitions will occur. These atomic transitions to higher binding energy states causes the emittance of a *characteristic X-rays*.

3.2. Dosimetric Quantities

3.2.1. Effective Atomic Number

The *atomic number* Z represents the number of positive charges (protons) present in an atomic nucleus. The elements or isotopes of the periodic table are defined by the atomic number. To carry out calculations depending on Z for composites of different elements one needs an equivalent: the *effective atomic number* Z_{eff}, which expresses an average atomic number for non-monoelemental materials. In literature, there are several proposed approaches for its calculation, including weighted mass averages, power law type formulas with experimental exponents etc. For the purpose of our experiments we quote the calculation of [4], according to which human tissue, air, water and acrylic glass have an effective atomic numbers of about

$$Z_{eff} \approx 7. \tag{3.13}$$

Therefore, measurements of dose to water can be considered comparable to dose in human (soft) tissue.

3.2.2. Stopping Power

As *stopping power* we define the average energy loss per unit distance travelled by a charged particle in a medium. The total stopping power $\left(\frac{dE}{dx}\right)_{tot}$ can be splited in two terms.
One term for describes the energy loss $(\frac{dE}{dx})_{col}$ due to inelastic collisions of the charged incident particle with the target atomic electrons. The second term expresses the radiative energy losses $(\frac{dE}{dx})_{rad}$, due to *Bremsstrahlung*.

$$(\frac{dE}{dx})_{tot} = (\frac{dE}{dx})_{col} + (\frac{dE}{dx})_{rad}. \tag{3.14}$$

Collisional stopping power can be calculated using the famous Bethe-Bloch formula. For electrons it takes the following form:

$$S_{col} = (\frac{dE}{dx})_{col} = \rho \cdot 4\pi r_e^2 \cdot m_0 c^2 \cdot \frac{Z}{u \cdot A} \cdot z^2 \cdot \frac{1}{\beta^2} \cdot R_{col}(\beta). \tag{3.15}$$

Constants in this equation are the classical electron radius $r_e (= 2.818 * 10^{-15}\, m)$, the rest mass of the electron $m_0 c^2 (= 0.511\, MeV)$, as well as the atomic mass unit $u (= 931,5\, MeV)$. The projectile's characteristics: the charge of the particle z and its speed v. For better readability, speed is given relative to the speed of light c: $\beta = \frac{v}{c}$. The residual function $R_{col}(\beta)$ is also dependent on the particle's speed and the ionization potential I of the material, plus higher order corrections. The characteristics of the absorber material Z, A and its density ρ complete the Bethe-Bloch-equation for electrons. The dimension of stopping power is energy loss per distance travelled, often quoted in $[S] = 1\, \frac{MeV}{cm}$.

3.2.2.1. Mass Stopping Power

Often the *mass stopping power* is used as a radiation related quantity. It takes into account the proportionality of stopping power and absorber density, making it approximately independent[3] of the absorber's density ρ:

$$\left(\frac{S}{\rho}\right)_{tot} = \left(\frac{S}{\rho}\right)_{col} + \left(\frac{S}{\rho}\right)_{rad}. \tag{3.16}$$

In literature the mass stopping power is expressed in units of energy divided by the mass dendity, usually given as $\left[\left(\frac{S}{\rho}\right)\right] = 1\, \frac{MeV * cm^2}{g}$.

[3] There is a minor dependency of the residual function $R_{col}(\beta)$ on ρ due to the so-called density effect which can be neglected for our experiments. Refer to [4]

3.2.2.2. Restricted Mass Stopping Power

For dose measurements though, not the (mass) stopping power is relevant, but the *restricted mass stopping power* $(\frac{S}{\rho})_{col,\Delta}$. The upper limit Δ of the energy considered is, by convention, given in units of eV and means that only events with energy losses below that limit are taken into account. This is due to the fact that the place, where an energy loss of the projectile occurs and the place that energy is absorbed by the target material are not necessarily the same. In dosimetry only the *locally* absorbed energy is relevant as a measurable quantity. Thus, bremsstrahlung and fast secondary particles, carrying the energy away from the place the initial event happened, are excluded.

For $\triangle \to \infty$ one obtains the *unrestricted mass stopping power*:

$$(\frac{S}{\rho})_{col,\triangle} \underset{\Delta\to\infty}{=} (\frac{S}{\rho})_{col}.$$

3.2.2.3. Linear Energy Transfer

Another important aspect when describing the energy transfer by ionizing radiation to a medium is the density of ionizations caused by a particular type of radiation. A way to describe this is the *Linear Energy Transfer (LET*, also commonly shortened to *L)*. It also makes use of the upper limit Δ and behaves quite similar to the collisional stopping power, although the definition is a bit different:

for charged particles of defined energy passing through matter the LET is defined as "the *average energy* dE_L *locally deposited* along the *track of length* dl":

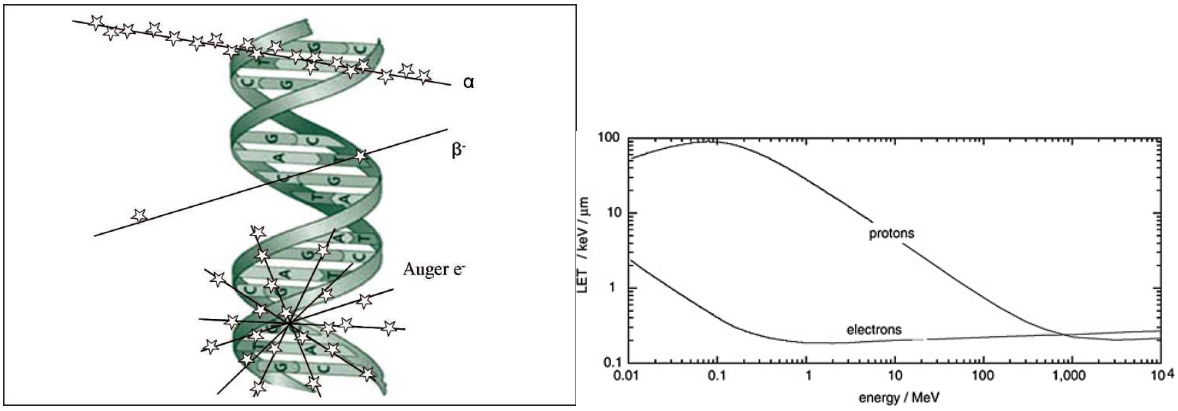
$$LET = \frac{dE_L}{dl}, \tag{3.17}$$

LET does not include interactions which deposit energy non-locally, such as the emission of delta electrons or, in the case of electron and positrons, radiative energy losses.

Just like S_{col} the LET increases for lower kinetic energy of the incident particles. The SI-unit of the LET is $[LET] = [L] = 1\,\frac{J}{m}$, although it is more commonly given in terms of $\frac{keV}{\mu m}$.

LET is often used to indicate the ability of a certain type and quality of radiation to inflict serious damage to living cells. By the numerical value of LET, ionizing radiation can be categorized as densely or non densely ionizing. The DNA double helix strand has a typical size of a few nanometers. To cause potentially irrepairable damage to the DNA structure, double strand break has to take place. Therefore two or more events within a distance of a few nanometers are desired.

Figure 3.2a on the following page shows schematically the ionization density of different radiation types. Figure 3.2b on the next page shows a comparison of LET values of protons and electrons as a function of the particle energy.



(a) A DNA double helix traversed by different particles. Each star marks an ionization event, schematically indicating the ionization density.

(b) LET for electrons and protons

Figure 3.2.: Linear Energy Transfer

3.2.3. Absorbed Dose

Absorbed dose D is the basic physical quantity used for radiological measurements. It is the energy deposited per unit of absorbing mass.

$$D = \frac{dE}{dm}. \tag{3.18}$$

The SI unit of absorbed dose is the Gray, which is defined as $[D] = 1\,Gy = 1\,\frac{J}{kg}$.

3.2.4. Equivalent Dose

The *equivalent dose* espresses the effect of absorbed dose on the human body, taking into account the different radiation qualities (particle types). A *weighting factor* w_R for the type of radiation is therefore introduced. The w_R for different qualities of radiation is based on experimental data, reflecting the discrepancies in biological effectiveness due to the differences in their LET[4]. Multiplying these weighting factors by the absorbed dose results in the *Equivalent Dose* H_T :

$$H_T = \sum_R w_R \cdot D_{T,R}. \tag{3.19}$$

Index T denotes the organ or tissue irradiated with the type of radiation given by the index R. Although the physical dimension is the same as for the absorbed dose, the SI unit *Sievert* (Sv) is used for equivalent dose to point out that it is a biological relevant quantity and not a purely physical one: $[H_T] = 1\,Sv = 1\,\frac{J}{kg}$.

Values for various types of radiation are given in table 3.1, while table 3.2 summarizes the dependence of the weighting factors on unrestricted LET values.

[4]among others, see ICRP 103 Appendix B or Krieger p. 320ff

Type of Radiation	Radiation Weighting Factor w_R
Photons	1
Electrons & Muons	1
Protons & charged Pions	2
Alpha Particles, Fission Fragments, Heavy Ions	20
Neutrons	Continuous Function of Neutron Energy

Table 3.1.: Radiation Weighting Factors

$L_\infty(\frac{keV}{\mu m})$ in water	$w_R(L)$
< 10	1
$10 - 100$	$0.32 * L - 2.2$
> 100	$\frac{300}{\sqrt{L}}$

Table 3.2.: Correlation of unrestricted LET L_∞ and weighting factors w_R

3.2.5. Effective Dose

The *effective dose* E takes into account the sensitivity of a given organ/tissue to the equivalent dose. The SI unit is again the Sievert to emphasize the biological meaning. The *tissue weighing factor* w_T is introduced to calculate E:

$$E = \sum_T w_T \cdot H_T. \tag{3.20}$$

Values of w_T for different organs are refined on a regular basis, the last time in 2007 in ICRP 103. See figure 3.3.

Tissue	w_T	$\sum w_T$
Bone-marrow (red), Colon, Lung, Stomach, Breast, Remainder Tissues	0.12	0.72
Gonads	0.08	0.08
Bladder, Oesophagus, Liver, Thyroid	0.04	0.16
Bone surface, Brain, Salivary glands, Skin	0.01	0.04

Table 3.3.: Tissue Weighting Factors (ICRP 103) w_T and sum over all tissues in the left column $\sum w_T$

4. Experimental Methods and Materials

The following sections will briefly describe the different methods and materials (detectors, calibration procedures, software tools) which will be used in the ensuing experiments. They also contain questions that should be answered during the experiment and documented in the report that will be submitted.

4.1. Strontium 90 (Sr-90)

For the purpose of this lab course, you will work with a pure beta-ray source made of Strontium-90 ($^{90}_{38}Sr$). The daughter nucleus after beta-decay is Yttrium-90 ($^{90}_{39}Y$).
When administered to the humans, both of these radioactive elements tend to concentrate in bones.[2], due to their chemical similarity to calcium[1].
As an artificial fission product, $^{90}_{38}Sr$ and its beta-decay product $^{90}_{39}Y$, almost the total amount of those isotopes found in the environment are man made. Sources of released material are nuclear weapon tests, nuclear events like Chernobyl (1984), as well as nuclear waste.

The decay chain is illustrated in figure 4.1. There you can see that $^{90}_{38}Sr$ beta decays to $^{90}_{39}Y$ at a 100% decay rate. This, in turn, is transmuted into the stable Zirconium-90 ($^{90}_{40}Zr$). The main mode of decaying is by beta-decay again. In fact, the gamma-decay of Yttrium-90 is so rare, that it can be neglected. Table 4.1 on the following page lists the relevant data for both radioactive nuclei. Additionally, in 4.2 on the next page the energy spectra for both nuclei are shown, as well as the overall energy spectrum.

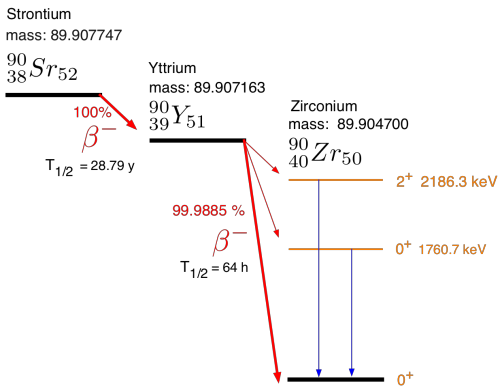


Figure 4.1.: Decay chain $^{90}_{38}Sr \rightarrow {}^{90}_{39}Y \rightarrow {}^{90}_{40}Zr$

In this experiment, the actual source is a small disc of diameter $d = 3\,mm$. It is made of a silver foil that has been injected with strontiumcarbonate. At the time of calibration in the year 2002 (exactly: at 9:47 a.m. on 11th May of 2002) the activity was $A = 33.3 \pm 10\%\,MBq$.

[1] Strontium and Calcium belong to the same group in the periodic table

Question 1: What is the activity A at the beginning of your experiments (t_{start})? Assume you will begin at 9 a.m.

Question 2: Using the calibrated activity and assuming that at the time of calibration t_0 the only source of activity was $^{90}_{38}Sr$. What number of Strontium-90 atoms have been present at t_0?

Sr-90			
$T_{\frac{1}{2}}$	$28.79 \pm 6\,a$		
β^-			
Avg. Energy $[keV]$	Max. Energy $[keV]$	Intensity $[\%]$	Daughter Level $[keV]$
195.8 ± 8	546.0 ± 14	100	0

Y-90			
$T_{\frac{1}{2}}$	$64 \pm 21\,h$		
β^-			
Avg. Energy $[keV]$	Max. Energy $[keV]$	Intensity $[\%]$	Daughter Level $[keV]$
25.0 ± 7	93.8 ± 16	$1.4E^{-6} \pm 3$	2186.282 ± 10
185.6 ± 10	519.4 ± 16	0.0115 ± 14	1760.72 ± 20
933.7 ± 12	2280.1 ± 16	99.9885 ± 14	0
γ			
2186.242 ± 25	2186.242 ± 25	$1.4E^{-6} \pm 3$	0

Table 4.1.: [**?**, **?**]Decay of Sr-90 and Y-90.
All ± signs in this table refer to the last valid digits.

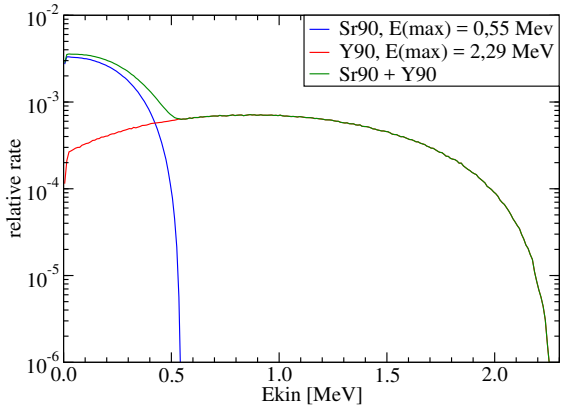


Figure 4.2.: Energy spectrum of Sr-90

Question 3: Making the same assumptions as before, calculate with respect to the total particle number at the time of calibration N_0
a)the percentage of $^{90}_{38}Sr$ atoms left,
b)the percentage of $^{90}_{39}Y$ present,
c)the percentage of $^{90}_{40}Zr$ present in the source at t_{start}

4.2. Radiation Detectors

There are several types of *radiation Detectors* in practical use, like ionization chambers, semi-conductor-based detectors and many others. In this experiment, an organic scintillation detector and gafchromic films are employed for measurements.

4.2.1. Scintillation Detectors

Scintillation detectors are based on the emittance of light after ionizing radiation has excited the detector's atoms or molecules. This is also known as *luminescence*. There are two types of luminescence, called *phosphorescence* and *fluorescence*. Phosphorescence means emittance with a time-delay (about $10^{-3} - 10^{2}\,s$), while with fluorescence photons are emitted instantly after excitation ($10^{-9} - 10^{-7}\,s$). Both types of detectors are widely used in practice. They are available in liquid, solid and even gaseous forms.

The emitted light is transferred through glass fibers to a photomultiplier. There, the light coming from the scintillator is converted to an electrical current by utilizing the photoelectric effect. Subsequently this current is amplified measured by the attached counting device.

In general, the characteristic properties of scintillation detectors are different for each type of ionizing radiation. The most important properties determining their quality and applications are:

- Conversion by fluorescence or phosphorescence
- State of matter
- Self-transparency for the emitted wavelengths
- Compatible indexes of refraction for coupling them with glass fibers
- Efficiency in converting the incident radiation energy to a flux of photons
- Linearity of conversion

4.2.1.1. Fluorescence Detectors

Fluorescence detectors provide almost real-time measurement of the impinging irradiation, due to their short emission times. One can distinguish them in inorganic and organic types.

The inorganic scintillators can only be manufactured from crystals, since their properties are governed by their crystalline structure and added impurities. Within these structures, energy bands exist, determining what quanta of energy can be absorbed and in what way such a high-energy state can be deexcited again. Inorganic scintillators generally are made of high-Z materials, increasing their sensitivity to gamma-rays.

Organic scintillators use a different approach. They are based on aromatic hydrocarbon molecules (low-Z) either disolved in a liquid or a plastic compound that provides a solid structure. Its the molecules themselves that are centers of fluorescence activity and not the underlying crystallic structure.

4.2.1.2. Organic Scintillators

The plastics serving as solvent for organic scintillation molecules can be manufactured to be water-equivalent, i.e. $Z \approx 7$. This means that the dose measured with these organic scintillators is comparable to the dose that would be deposited in human soft tissue. In addition, the conversion speed of incident radiation to emitted as light is in the scale of nanoseconds. Transparency to the emitted photons is, in contrast to inorganic crystals, no issue with these devices, see figure 4.3.

Disadvantages in comparison to inorganic scintillation crystals are the low scintillation efficiency, i.e. low light output, as well as their lower sensitivity to gamma-ray energies below $100\,keV$. To compensate for the low light output, a good photomultiplier is required, while sensitivity to incident photons increases increasing the thickness.

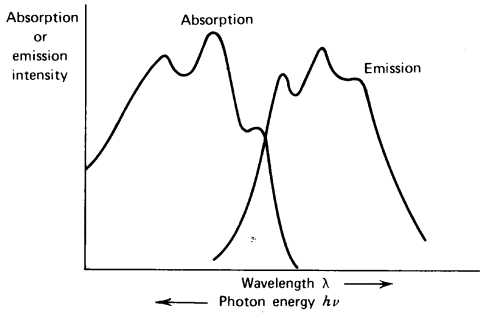


Figure 4.3.: Absorption and emission spectra of a typical organic scintillator

4.2.1.3. Optidos™-system

The Optidos™ scintillation detector system by PTW Freiburg[2] has been designed for the purpose of quality assurance and dose verification in brachytherapy. It features an organic scintillation detector made of water-equivalent plastics with increased sensitivity for low energy photons and very good linearity for electrons. A radioactive check source is

[2] https://www.ptw.de

avaialable and will be used in order to compensate for the decrease in detector sensitivity over time.

The detection system consists of four parts:

1. Scintillation-detector Type 60006 with a glass fiber attached
2. Scintillation-dosimeter Optidos Type 10013
3. Calibration-phantom (water-equivalent)
4. Check source (Sr-90)

4.2.1.4. Scintillation-Detector Type 60006

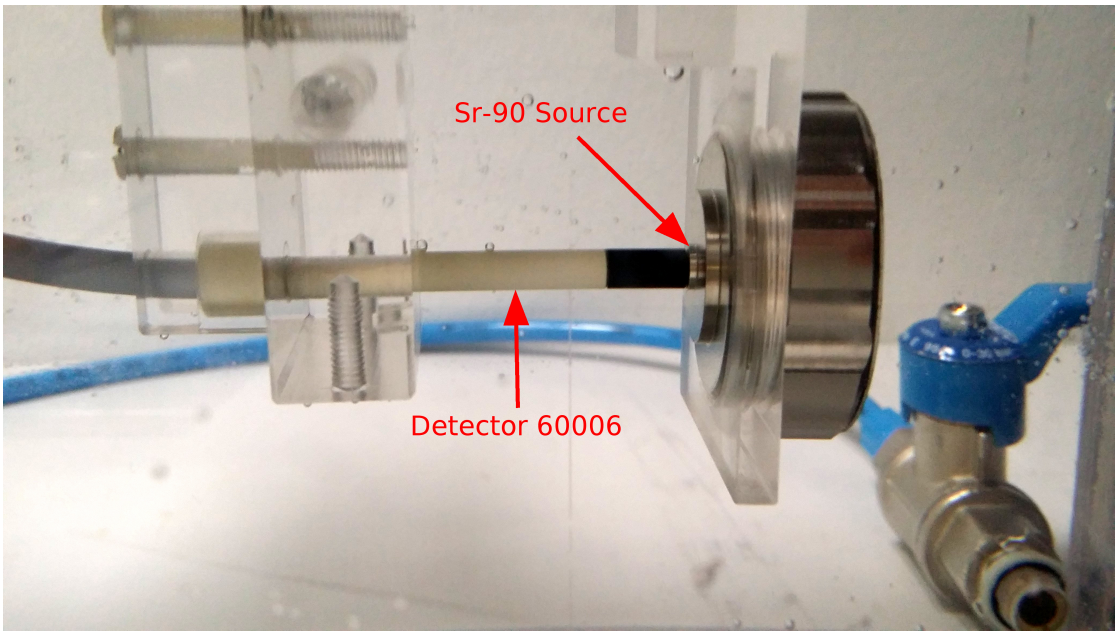


Figure 4.4.: Detector Type 60006 with check source in water phantom

The scintillation-detector Type 60006 contains a cylindrical standard organic scintillator[3] with a diameter of $1\,mm$ and a height of $1\,mm$. The active detection volume amounts to $0.8\,mm^3$. It sits $0.4\,mm$ behind the front edge of the detector assembly. Figure 4.5 on the next page shows the result of a Monte Carlo simulation of the detector tip in water, simulating electrons[4] of up to $3\,MeV$. The colorbar shows the comparison of the deposited dose in the detector material to that deposited in water. For each material marked in the figure, the corresponding density is denoted next to its name. As you

[3] One of the most commonly used organic scintillators: The Bicron Corp. "BC-400"

[4] The manufacturer of the scintillation crystal actually states a correction factor of 1.03 for readings from a Sr-90 source due to minor deviations from linearity in event-to-light conversion for low-energy electrons. This is already taken into account during calibration

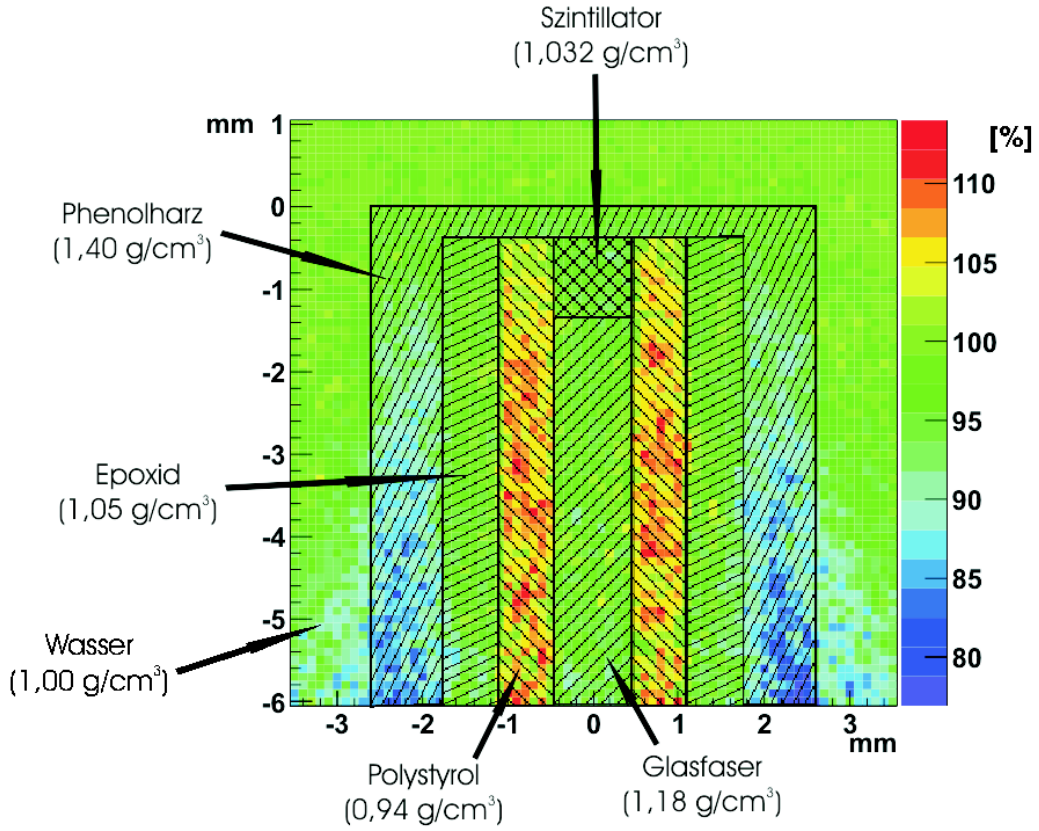


Figure 4.5.: Geant4-simulation of dose deposited in the scintillator Type 60006 compared to the dose that would be deposited in water
Dose to water = 100%

can see, close to the organic scintillator there is no major difference in deposited dose. Behind it though, the denser phenol resin as well as the less dense polystyrene display larger discrepancies. Therefore, it is recommended to point the tip of the scintillator towards the source during the measurements.

4.2.1.5. Dosimeter Optidos Type 10013

When light enters the dosimeter through the glass fiber, a photomultiplier converts it to electrical current and amplifies it. This means that the Optidos Type 10013 device does not count single events, but measures the stream of photons. As a result the maximum accuracy of 0.5% can only be provided down to a lower dose rate limit of $\overset{\circ}{D} = 0.4\,\frac{mGy}{s}$. The upper limit for precise measurements is $\overset{\circ}{D} = 0.4\,\frac{Gy}{s}$. At this point the photomultiplier is saturated.

Preceding any measurements, the dosimeter has to be calibrated to obtain the absolute dose deposited in water. There are two types of calibrations.

To compensate for deviations in environmental variables and background radiation, as well as for the aging process of the device, it is mandatory to determine a correction factor k_m before performing measurements.

1. A basic calibration is performed every two years by the manufacturer. During this procedure, the *displayed check value* $k_{p,0}$ is determined. $k_{p,0}$ is the dose-rate $\dot{D}$ in units of $\frac{Gy}{min}$ displayed by the Optidos device after irradiation for $60\,s$ using the check-source. The most recent Certificate of Calibration[5], i.e. the documentation of the last calibration, can be found in the laboratory. Before your measurements, you have to calculate k_p from this by applying the law of radioactive decay on the source (see equation 3.2 on page 5)

2. To compensate for environmental variables affecting the measurements, you have to perform a gaging. This is achieved by first performing a test-run for $60\,s$ without any source of radiation. The value displayed by the Optidos device should be less than $0.5\% \cdot k_{p,0}$. Subsequently another measurement is performed, this time with the check source, for $60\,s$. The result of this measurement is the *correction factor* k_m. In the calibration relation used by the software of the Optidos device, k_p over k_m is used to account for different measurement conditions in comparison to those during basic calibration.

Based on the aforementioned procedure, the calibration relation to transform the measurement displayed by the Optidos to dose to water is:

$$D_W = k_Q * \frac{k_p}{k_m} * N_W * M. \quad (4.1)$$

D_W : dose to water

k_Q : correction factor for beam quality (type and energy of radiation, $k_{Q,Sr90} = 1.03$)

k_p : expected displayed check reading after $60\,s$ of irradiation

k_m : measured value after $60\,s$ of irradiation with the check source

N_W : calibration factor for dose to water (= 1)

M : displayed value

[5] "Kalibrierschein"

Question 4: Using $k_{p,0}$, calculate the expected k_p on the day of your experiment.

Values (Detector Serial-Number: 000058, Optidos Serial-Number: 000037):

- Date of calibration: 13. October 2015
- $k_{p,0} = 1171.0\,\frac{mGy}{min}$
- $T_{\frac{1}{2}}(^{90}Sr) = 28.79\,y$

Software (LabView)

For automated measurements at multiple points in space defined by a raster (*grid-scans*) with the Optidos you will use a software called "Optidos_Gridscan". It is written in LabView (National Instruments), a graphical programming language commonly used for measurement and automation tasks. In LabView, programs and sub-routines are referred to as *virtual instruments* (VIs). Optidos_Gridscan includes, among others, VIs for serial communication with the Optidos device and controlling of the three-axis stepping motor stage. It brings them together in a GUI, enabling you to perform automated grid-scans for dose measurements in three dimensional space.

It also includes a simple implementation for visualization of the acquired scans. This allows the user to quickly estimate the center of the source measured in terms of detector position variables.

4.2.2. Radiochromic Films

Radiochromic films (RCF), also referred to as Gafchromic, the trademark of the main manufacturer Ashland, are used in radiation therapy and treatment planning since 1984. Originally limited to high-dose applications like treatment of food packaging and sterilization of medical equipment, RCF have become popular since the emergence of the EBT[6] type films by Ashland in 2005, as these provide clinically relevant dose ranges (EBT 1: $0.01 - 8\,Gy$) . As the main requirement for their usage are a good scanning device with transmission mode capability, they pose an affordable alternative to other detector systems. The sheets of EBT film are flexible, can be cut to the desired size and are able to withstand water for several hours. In comparison to radiographic films (comparable to old photographic films), they neither need to be stored in dark rooms, nor must they be developed using chemicals. As they are self-developing, they provide a convenient way of *Quality Assurance* (QA) in treatment planning. Their main application in clinical routine is the verification of treatment plan conformity of radiation treatments with high dose gradients.

The main part of a radiochromic film is its *active layer*. It is a thin coating of a radiosensitive chemical substance, which is enveloped between two protective layers. These layers, usually made of transparent plastics, keep the active layer in place and may well

[6] *External Beam Therapy*

provide and improve other aspects of the whole film structure, like stability, flexibility, water resistance, etc., that generally improve the handling of RCF.
The active layer changes color as consequence of exposure to ionizing radiation[7]. In general, it is based on crystalline polyacetylenes. Figure 4.8 shows a schematic representation of a modern active layer.

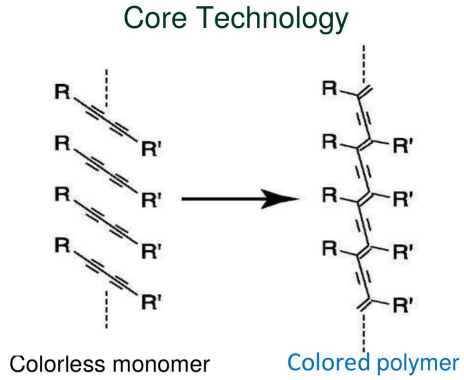


Figure 4.6.: Schematic of the polymerization

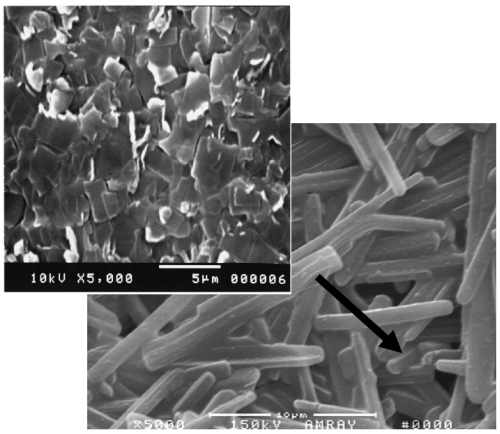


Figure 4.7.: Lithium poly-diacetylene. Each "rod" is a single molecule

Figure 4.8.: Poly-diacetylene

The underlying physical process is the polymerization of the diacetylene monomers into acetylene polymers, meaning that the rod-like monomers form intra-molecular bonds(i.e. they polymerize). These bonds cause the initially optically transparent active layer to acquire a characteristic blue color, since light absorption in the visible spectrum is increased. This is especially true for the red wavelengths[8].
The highest exposure, the longer these polymer chains become, causing an intenserer coloring of the film. What the human eye interprets as darkening and intenser color, can physically be described using the *optical density* OD,

$$OD = \log \frac{1}{T}. \tag{4.2}$$

it is the logarithm of the inverse *transmitted intensity* T. A scanning device with a transmission unit will use its (white) source of light to acquire values of transmitted intensity. An increased optical density means that less light will be transmitted through the film.

During the process of scanning, each small area measured is assigned a value. These small quadratic areas over which the scanner's CCD-chip measurements are averaged,

[7] heating and UV light have the same effects, but in modern films the other layers provide good protection against them
[8] maximum absorption for EBT-type films is around $633\,nm$, see figure 4.9

are called *pixels*. Scanning a radiochromic film will thus provide a matrix of pixel values with a constant pixel size given in units of *dpi* (dots per inch[9]).

Pixel values may be given in terms of RGB values. In pictures scanned with a color depth of forty eight bit, each of the *R*ed, *G*reen and *B*lue channels can assume values ranging from 0 up to 2^{16} (= 16 bit), ranging from no transmission to full transmission:

$$0 \leq \begin{matrix} Red \\ Green \\ Blue \end{matrix} color\ value \leq 2^{16} = 65535.$$

To measure the effect of irradiation on radiochromic films, the pixel values of irradiated films need to be compared to the pixel values of not irradiated ones from the same production batch (lot number). Introducing the effective optical density *netOD*, the difference in optical density before and after exposure,

$$netOD = OD_{irr} - OD_{not} = -\log\left(\frac{PV_{irr}}{PV_{not}}\right). \tag{4.3}$$

The indexes stand for (*not*) *irr*adiated and PV is used as abbreviation for pixel value.

Having calculated the value of netOD, only one more step is necessary to acquire the desired *dose* values from measurements with radiochromic films. The reaction of the films to the energy deposited needs to be calibrated. At the chair for experimental medical physics this is usually done by irradiating films of the same type and production date ("lot number") at a linear accelerator while using an ionization chamber as a dose reference during the irradiation of the calibration films. After that procedure, the netOD is correlated to the measured dose and a calibration curve is fitted to the values.

Depending on the dose delivered it is feasible to use only one (the red) or all three of the RGB color channels. Dose measurements that will be performed in this lab course can be restricted to the red channel, as recent literature states up to 20 Gy as upper limits for single channel dosimetry.

A very important aspect to be mentioned is the averaging nature of radiochromic films. Various studies have shown that films of the EBT type are very precise dosimeters for absolute doses under the premises of homogeneous fields irradiating large enough pieces of film. This comes from fact that for absolute dose measurements one chooses large regions of interest (ROI) to analyze in a piece of film. Analysis is then done by creating a histogram including as many pixels as possible avoiding the edges of the film, as well as the boundaries of the irradiation field. An example from clinical practice would be pieces of 4 by 5 cm irradiated by a linear accelerator with a field size of 10 by 10 cm. Assuming the films are scanned with a resolution of 150 dpi, the length of a pixel amounts

[9] $1\,in = 2.54\,cm$

to 0.169 mm. A typical region of interest in this case might be 2.5 by 2.5 cm which would include more than $2 \cdot 10^4$ $pixels$. Averaging over such a number of single measurements in a homogeneous field would yield very stable mean values from a statistical point of view.

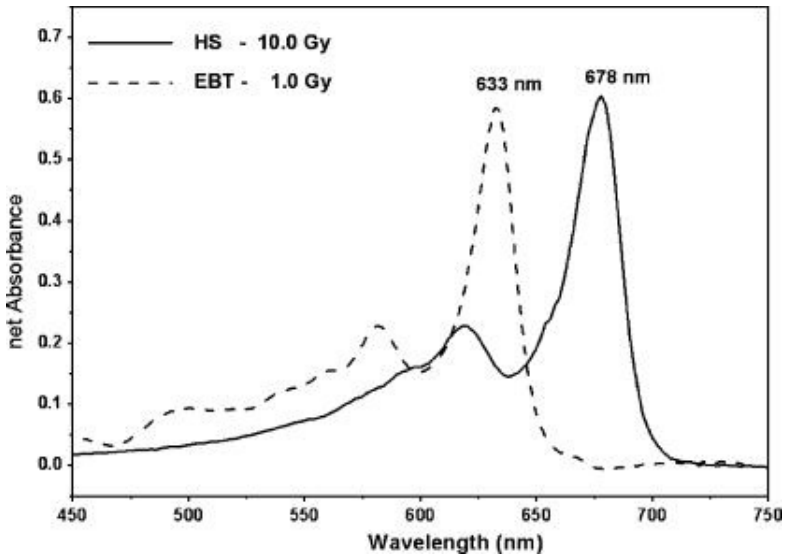


Figure 4.9.: netAbsorbance for EBT and the older HS radiochromic films. Note the tenfold increase in sensitivity of EBT over HS[3].

The general characteristics/advantages of radiochromic film dosimetry in comparison to other methods are:

- 2D-dose measurement
- high spatial resolution
- linear dose and energy dependence
- water equivalence
- low technical requirements (scanner)
- easy handling
- only one calibration needed per lot

4.3. Monte Carlo simulation

Monte Carlo simulation of particle interactions with matter are computer algorithms based on the random sampling from known probability distributions on the microscopic scale to obtain macroscopic results, e.g. interactions of electrons with matter to obtain the macroscopic quantity of dose deposited in water.

Monte Carlo algorithms are commonly used to accurately simulate experiments that are either difficult/not possible to be repeatedly performed (ie dose calculations in patients) or to predict physical quantities before the actual experiment (ie radation protection calculations for shielding design of large facilities). Accurate physical models and detailed look-up tables of experimental data are required, in order to reliably reproduce complex physical processes.

The following is a general scheme of Monte Carlo Experiments in physics, performed for every single particle simulated:

1. Select a particle coming out of the source to be simulated
2. Sample from total cross section distributions to determine the distance to the next interaction (step length)
3. Determine the type of interaction by sampling from partial cross section distributions
4. Determine if there is a secondary particle produced by the interaction. If yes, define its properties (direction, energy, momentum etc) by sampling from the appropriate distributions and update the properties of the initial particle (direction, energy, momentum etc)
5. Repeat steps 1-4 until all particles have been absorbed, have their energy dropped below a certain threshold or come at rest, or have left the area of simulation

4.3.1. FLUKA & FLAIR

In the context of this lab course FLUKA[10](FLUktuierende KAskade) will be used for simulating our experiment in the water tank. FLUKA is written in Fortran[11]. By using a GUI for FLUKA called FLAIR[12] (FLUKA Advanced Interface), the necessary simulations can be performed without the need to code in Fortran.

The FLUKA software can be used without FLAIR too. All input parameters to the simulation are provided in the form of the so-called data cards separated by delimiters[13]. This method is very cumbersome and error prone. Therefore, the graphical user-interface FLAIR will be used for the purposes of this lab course. The input file is still based on the aforementioned cards, but FLAIR is automatically creating, starting from the user specified options defined in the graphical interface (filling of predefined fields, choosing options from drop-down menus etc).

[10] http://www.fluka.org/fluka.php
[11] Note that Fortran can only handle names of up to 8 letters/digits length
[12] http://www.fluka.org/FLUKA/flair/
[13] e.g. spaces

In general, the input file contains three different types of information:

1. Source/particle information. This usually defines the type of source particles, their kinematic distributions, the number of particles (primaries) to be simulated, etc
2. Geometrical and material descriptions. This usually includes volumes (rectangular water tank), positions and materials (water, plexiglass etc)
3. Cards defining the scorers. The latter record the required information (ie 3D dose distrubution)

There is an input file prepared for you. All parameters are set to resemble your real experiment performed in the water tank. The only required mofifications concern the USRBINs (volumes of scoring dose to water) and they will be described in the next chapter. Note that FLUKA results are always reflects normalized per primary particle.

5. Experimental Procedure

5.1. Notes

Keep a detailed record of all the steps and measurements in the lab. This will allow you to trace back any sources of errors/problems and it will be the basis of the report you will have to submit for your evaluation.

The proposed experimental steps are the following (red for the film experiment, blue for the Optidos/scintillator experiment and black for generic steps) and they will be detailed in the coming pages:

1. Make sure that Optidos is powered on
2. Prepare the film-stack
3. Irradiate the film-stack
4. Calibrate Optidos
5. Prepare the scintillator detector set-up for measurements in water
6. Find the center of the source
7. Conduct the two short OPTIDOS measurements
8. Start the long OPTIDOS measurement
9. Simulate the Optidos measurements with FLUKA
10. Calculate your calibration curve for the gafchromic films with Matlab
11. Scan the films
12. Use Matlab to extract histograms/profiles from the digitized films
13. Perform the analysis (to be completed at home)
14. Write a comprehensive report

5.2. Grid Scans Using the Optidos Device

Note: The Optidos device should be switched on at least 30 minutes before the calibration procedure is started!

Aim: Acquire a three dimensional dose distribution

The aim of this experiment is to obtain a three dimensional dose distribution by performing point-wise measurements with the scintillation detector attached to the Optidos device. You will later compare your results to a simulation carried out with FLUKA. Several intermediate steps are required before you can actually obtain a comprehensive data set of absolute dose values.

1. Calibrate the Optidos,
2. Find the center of the check source,
3. Acquire a depth-dose curve,
4. Perform the grid scan.

Never bend the optical fiber with a radius less than 10cm!

Instruction 1 Starting LabView

1. Log into the OPTIDOS-workstation using the log-in credentials at the computer,
2. Navigate to 'Y:\project\prakt-dosimetry\Work\Groups' (Shortcut on the Desktop),
3. Create a folder with your last names. You will save all your data here!
4. Go to 'Y:\project\prakt-dosimetry\Work\Software\LabView',
5. Run the 'Optidos_Gridscan.exe'.

The GUI of the VI will open (see figure 5.1 on page 32).

To calibrate the Optidos, you have to measure the background and then determine the value of k_m.

Instruction 2 Calibrating the Optidos Device

Everything related to the Optidos detector system is organized in the tab labeled Optidos.

1. Click Connect (1) to connect to the system.
2. The calibration process is started by clicking calibrate (2).
3. What is your calculated value of k_p?
   Click OK.
4. Follow the on-screen instructions. They appear in a yellow box at the bottom of the screen.

You need to get your supervisor during the calibration procedure. He has to put the source into the calibration phantom. After calibration is done he will put it into the water basin.

Use the acrylic walls to protect yourself from radiation!

Refer to figure 2 and follow the instructions on screen.
When the calibration is done you have to change the set-up. Let your supervisor remove the calibration source from the plastic phantom. He will then attach it into the acrylic holder and put the mounted sourced into the water tank.

Instruction 3 Preparing Optidos Measurements

1. Close the drain at the bottom, then fill the water tank,
2. Put the motor-stage on top of it,
3. Remove the scintillator from the plastic phantom,
4. Carefully thread it, including the fiber, under the stage,
5. Using the plastic screws, mount it in the dedicated holder,
6. Screw the detector holder to the stage.

When everything is put together you can perform your first test run.

Instruction 4 Task: Find the Central Axis of the Source!

1. In the field called Motor Control click Connect Motors and wait for the stage to self-adjust,
2. Validate the directions by using the directional buttons,
3. Start a 10 second manual measurement clicking Start Manual Measurement,
4. In the upper right corner there's the tab called Grid-Scan. Refer to the pictured cube on page 33 for an explanation of the variables. "Estimated Duration" will show you the estimated time of the measurement,
5. Now try to move the scintillator as close to the center of the source as possible by visual guidance, using the Manual Control.
6. In Optidos set the "Timer" to 5 seconds,
7. Enter the following data for your first estimation of the source's center:

$$\begin{array}{ccc} x_0 & l_x & d_x \\ 16 & 10 & 0,5 \\ y_0 & l_y & d_y \\ 21 & 10 & 0,5 \\ z_0 & l_z & d_x \\ 0 & 0 & 0 \end{array} \tag{5.1}$$

   Attention: These values are certainly far off the central axis! You could try to find better starting values by estimating the center visually!
8. Start the grid-scan by hitting Set Grid, followed by Start Grid-Scan.
9. When the scan is finished you're supposed to choose a .txt-file to save the recorded data. Do this by clicking the folder-icon on the bottom of the screen, enter a filename and finish by clicking Save.
10. To evaluate the measurement click Evaluate Grid-Scans at the bottom of the VIs front panel.
11. Load the recently created text file and use the "Profile" tab on the right hand side to inspect the profiles of your scan.
12. Repeat the whole procedure (steps 7 to 11 with improved grid-scan values) until you're satisfied with the precision.
13. Finally, write down the coordinates you suspect to be the center of the Sr-90 source. You will need it for the subsequent measurements!

Question 5: Measurements to Perform with the Optidos

After finding the central axis of the source, you are supposed to perform three measurements:

1. A depth dose curve with a step-size of $1\,mm$. The Grid should look like this:

$$\begin{array}{ccc} x_0 & l_x & d_x \\ 16 & 0 & 0,5 \\ y_0 & l_y & d_y \\ 21 & 0 & 0,5 \\ z_0 & l_z & d_x \\ 0 & 20 & 1 \end{array} \tag{5.2}$$

   These values assume the central axis to be at $(x, y) = (16, 21)$ and a maximum range of the electrons of $2\,cm$!

2. A second depth dose curve with increased precision,

3. A scan of several planes perpendicular to the central axis to characterize the source in 2d/3d.
   Plane-Scans of approximately $5\,mm$ in all 3 directions. Within the planes use a step-size of $1\,mm$ in each direction. For the Depth use the same value as in the scan before.

For these scans please make the following settings in Optidos:

Instruction 5 Optidos Settings for Grid-Scans

- "Range": "low" or "auto"
- "Timer": 60
- "Unit": Gy
- "Timer": on

Save each run's data in a separate txt-file.

5.3. FLUKA-Simulation

While the LabView VI runs the long grid-scan, you will simulate the expected dose-distribution using the MonteCarlo-Code of FLUKA.

To do this, you first have to connect to a Linux workstation. On the desktop you will see an item called "FLUKA.rdp". Double-clicking it initiates the remote desktop

connection[1] to a Linux workstation. Use the same login credentials as you did for Windows and check that the module "sesman-Xvnc" is used.

Accessing FLAIR is done via console. Use the shortcut to "console" on your Linux desktop and enter "flair".

Now you should see the main window. As shown in Fig (Figure) click "Open" and load the file "praktikum.flair" you can find in the "Software/Fluka" folder. In the top menu bar you can take a look at "Input" and "Geometry" to see the actual set-up. After inspecting those two tabs please return to the main tab and reload the project, since it's very easy to change the set-up with some ill-thought clicks in those tabs. The simulated geometry consists of a Sr-90-source in water, which is confined in an acrylic case without lid. The so-called water phantom is placed in air and to keep it in line with FLUKAs demands the sphere of air is surrounded by a big "black hole"[2]. So the simulated environment is pretty close to your real-life experiment.

Before running the simulation, please save your personal version of the project by using "Save" and creating a new "*.flair" file in your Groups directory.
Now you have to adjust the two so-called USRBINs. These are the volumes of your virtual detectors. Take a look at picture [USRBINs]. Try to replicate your measurements with the Optidos by implementing the same scanning patterns used as USRBINs. Keep in mind that the scintillation detector has a certain volume of detection that should be reflected in the simulation.

The number of simulated decays is set to 10000. Increasing it only improves the statistics while prolonging the calculations. The FLUKA-output is always normalized to a single particle.

Question 6: How do you compare the simulation of a single decay to your real source?

Starting the actual simulation requires you to choose the "Run"-tab from the menu-bar. Settings here need not be changed as there are 5 runs, each consisting of 10000 decays, preset. Just hit the "Start"-button and wait for FLUKA to finish the simulation. When done, look at "Data". It should look similar to Figure (Figure). By clicking "Process" you compile the runs to one data set. Go back to "Files", choose the "data"-type and select the *.bnn file. Hit the "Convert file to Ascii"-button and a file named *.bnn.lis will be created(see Figure(Figure)). This is the file you will need for your analysis!

[1] Hint: To switch between full-screen and windowed mode use CTRL + ALT + ENTER
[2] the black hole is used to destroy particles leaving the volume of interest for simulation.

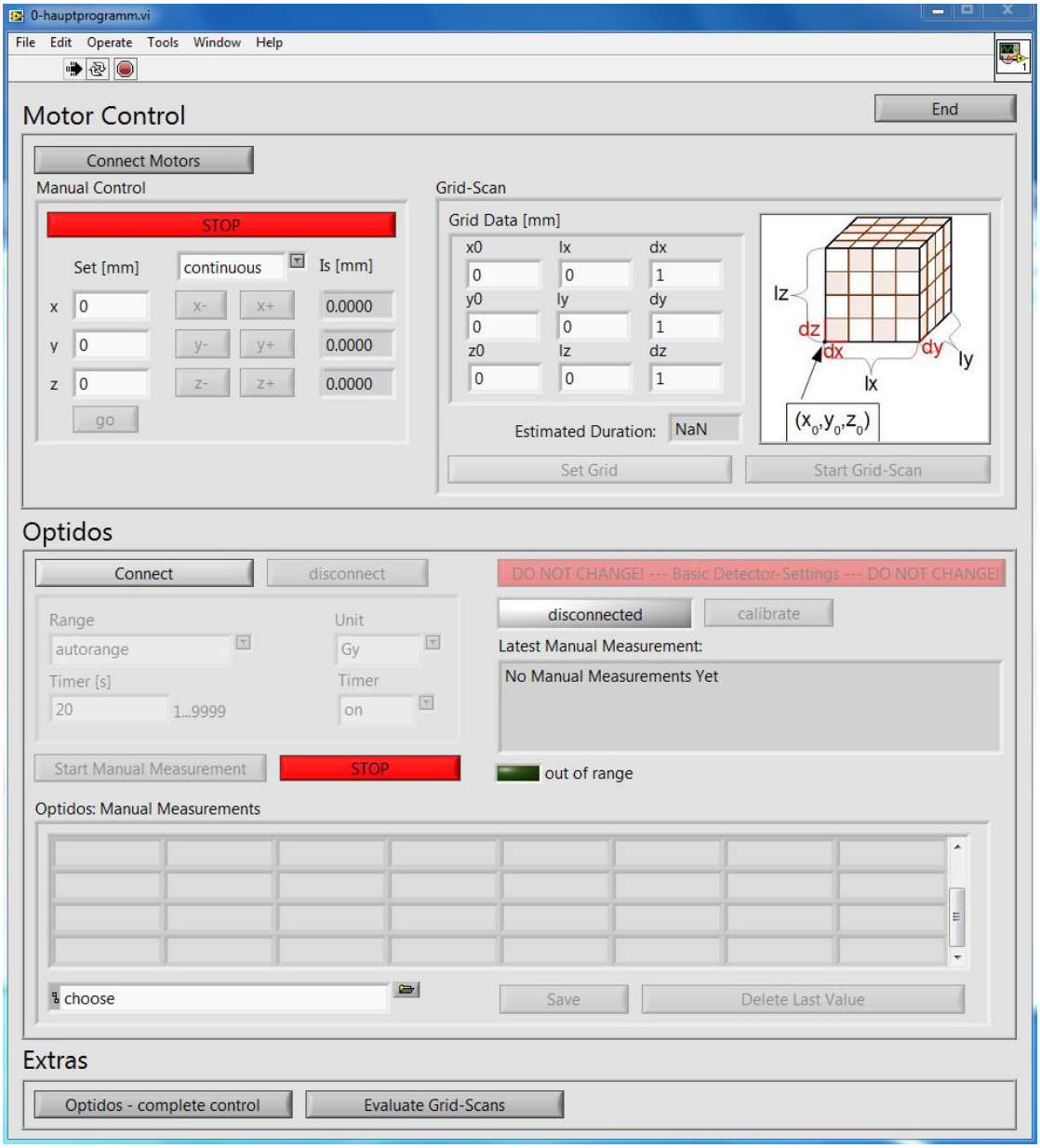


Figure 5.1.: OptidosGrid-VI

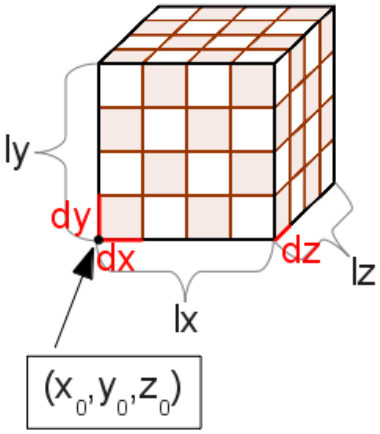


Figure 5.2: Grid-Scan legend (cube)
x_0 : starting coordinate
dx : step-length in x-direction
lx : path-length in x-direction
Check if the axes are the same for your experiment!

6. Data Analysis

6.1. In the Lab

6.1.1. Films

The general work flow to acquire dose values from measurements with radiochromic films is the following:

$$\text{Scanning} \longrightarrow \text{Red Color Value} \overset{background}{\longrightarrow} \text{netOD} \overset{calibration}{\longrightarrow} \text{Dose}$$

By creating your calibration curve from the digitized calibration films in the folder "Calibrationdata", you will learn how to extract the red channel color values from the unirradiated background sheets. These will then be used to determine the netODs of the calibration films. Plotting the dose values provided in a text file against the corresponding netODs will then enable you to fit a calibration curve.

To begin the analysis of the scanned films click the "Matlab" icon on the desktop.

Environment-variables are set-up and you can get on the task of calculating a calibration-function right away.

Be aware that you can save all variables in your workspace in the "Home" tab by clicking "Save Workspace"!

6.1.1.1. Calibration Curve

Take a look at the Main area. "ImgDataGui.m" and "calibration.txt" are preloaded. In the text-file you can see which number of the film was irradiated with what dose in mGy. Two of the films have not been irradiated to evaluate the background.

Instruction 6 Extracting the red channel values of the calibration background

Open the App "ImgDataGUI" in the top bar. The GUI used for the analysis of gafchromic films shows up. Go to "File" -¿ "open" and choose the "Calibrationdata" folder. The films in there have been scanned in landscape mode with a resolution of 72 *dpi*. Select the .tif files corresponding to background measurements and load them. Extracting the red channel values is straight forward:

1. Select the picture to analyze in the upper left box
2. Choose a rectangular ROI (Region Of Interest) from the tool bar and create a large mask by dragging the pointer while holding down the left mouse button. Due to a bug in the GUI you need to double-click the ROI before performing any analysis!
3. You can also move that ROI by clicking and holding it.
4. Create the histogram ("Analysis" -¿ "Plot histogram").
5. A separate window for the plot will open. Write down the mean values and errors for your lab protocol, then close the plot.
6. A box will appear asking you if the histogram should be used as a result, click "yes". This will add it to the "result" variable you save later on.
7. Do the same for the second piece of background film.
8. Before closing the GUI, select "Analysis" -¿ "Save Results" and enter an appropriate name to save your results.

When you're done extracting the two histograms for red color background values, close the GUI and return to MATLAB's main window. On the left-hand side, the folder pane, double click the newly created file. On the opposite side of the screen, you can see the variables pane. Choose and open the variable "result" that you just loaded. You will now employ the MATLAB command "mean" to calculate the mean background of the calibration films.

The following code first renames the variable result and then calculates both mean values for the respective histograms:

Algorithm 6.1 Calculating mean values using Matlab

```
#copy variable result to variable background since result will be overwritten automatically
background = result
#calculate mean of column 1 (histogram values) of background to new variable bkg_mean
#Parenthesis explained: (row ; column) and (: , 1) = all rows of column 1
bkg_mean(1 , 1) = mean(background(: , 1))
#add the mean of column 2 (corresponding errors) to column 2
bkg_mean(1 , 2) = mean(background(: , 2))
```

When done, restart the GUI and open the pictures of all the other calibration films[1].

Instruction 7 Extracting netOD for calibration

1. Load the other calibration films,
2. Go to "EBT" -¿ "New background value" to enter your averaged background red color value,
3. Switch to "EBT" -¿ "Calculate Optical Density" or choose the corresponding button above the image displayed. This will provide the netOD of the films,
4. Follow the procedure of analysis given in Listing 6 on the preceding page.

Fitting the Curve

MATLAB includes a fitting tool called "Curve Fitting". Start it by switching tabs at the top of the screen to "APPS". Then choose "Curve Fitting". After creating a table of dose per film, plot it against the netOD data. As stated in the theoretical part of this manual, the fitting function for dose over netOD is:

$$D(netOD) = a * netOD + b * netOD^c \tag{6.1}$$

[1] **Hint:** Holding down Strg or Ctrl while clicking the left mouse-button does the trick

Instruction 8 Using the Curve Fitting tool of Matlab

1. If not already there, load the variable "Calibration_Doses" (units are mGy) from the file "Calibration_Doses.mat" into the workspace,
2. Open the App "Curve Fitting",
3. Choose your netOD data for X ("netOD = result(:,1)"), Calibration_Doses for Y data,
4. Set the type of fit to "Custom Equation" and enter the calibration formula 6.1 on the previous page,
5. Check your R-square value: It is the main measure of the quality of the fit! You should at least acquire $R^2 \geqslant 0.9995$,
6. It might help to set boundaries for the coefficient c of $\begin{cases} c_{max} = 3 \\ c_{min} = 2 \end{cases}$. To do this, click the button Fit Options... to enter the boundaries,
7. Write down the coefficients etc. and save the fit to your workspace,
8. Should you need it again, just reopen the curve fitting tool and reload the files.

6.1.1.2. Obtaining Absolute Dose

Now it is time to obtain absolute dose values. To get there, you need to determine the background value of your films first. The unexposed piece of film is used for this. Subsequently you can enter the background value and calibration coefficients to directly obtain the absolute dose values of your films.

Instruction 9 Analyze your films

1. Return to the GUI (the best option is to restart it to make it flush any saved values),
2. Load the unexposed piece of film and determine the background.
3. Choose "EBT" -¿ "Create new calibration" to enter your calibration coefficients and save the calibration as "filename.cal.mat",
4. Load the films from your experiment and select the one that was closest to the source,
5. Choose "Manual ROI", then Ellipse and enter the following values:

x	10
y	10
$\emptyset x$	30
$\emptyset y$	30

,
6. Move the ROI by pressing and holding down the left mouse-button,
7. If the mask does not fit the irradiated area, define other values,
8. Check if the profiles in x- and y-direction indicate that your ROI covers the irradiated area, while keeping it as small as possible,
9. Save the profiles as pictures, then create the histogram. Save it as a picture, too,
10. Repeat this step for film the furthest removed from the source!
11. Restart the GUI, enter the background value and load your calibration curve.
12. Do the histogram analysis with "View" -¿ "Dose" selected for all your films, maintaining the same diameter of ROI.
13. Create a plot of the histograms mean values over the distance from the source.

Hint: In the console your histograms values together with ROI-data are parsed. Copy & paste them into a textfile (e.g. with notepad++ or in matlab directly). This will help you with reconstructing the initial ROIs.

6.1.1.3. Analysis

For further analysis you are encouraged to use Matlab but you are free to choose the tools you prefer, too! As you can access your data and Matlab via remote login for two weeks after your day at the lab, some more instructions for Matlab will be given in the following paragraph.

For simple plots in Matlab there are several commands. Most of them can be investigated using the plot catalog. Using the Matlab Help is also very handy, as you can

look up any command just by selecting and right-clicking it. One of the most important plots is the plotting with errorbars. That is why they are briefly explained in 6.2.

Algorithm 6.2 Simple Plotting with Error Bars in Matlab

#Suppose you want to plot the average dose values D from your histograms with corresponding deviations d over the number of each film
#D and d are one dimensional arrays, combined in the matrix Dose it would look like this:
D = Dose(:,1);
d = Dose(:,2);
#The number of elements in D shall for example be 12. To represent the 12 films you need an 1-d array ranging from 1 to 12 with increments of 1.
number = [1:1:12];
#Means the array number starts with 1,each incremental step is +1 and the maximum value equals 12.
#To plot the desired figure use the command "errorbar(X,Y,$\triangle Y$)":
errorbar(number,D,d);
#You can now change the properties of your plot by selecting "View"-¿"Property Editor"

Optidos You can analyze your Optidos data in the same Matlab GUI as the films. Select the text files containing the data and evaluate the dose map.

To import the Optidos data into the workspace, please follow the instructions in 10.

Instruction 10 Importing Optidos Data

1.Right-Click an Optidos-text-file and choose "import",
2.Import the data,
3."NewVariable=horzcat(value1,value2,value3,....)"

6.1.2. Minimum Data

Make sure that have at least acquired the following data if you want to perform the analysis using other tools:

- Optidos: A txt-file for each run
- Radiochromic films: The Scans and all your MATLAB files (in a readable format! .m-files are proprietary)
- FLUKA/FLAIR: The outputfile in ascii-format

6.1.3. Remote Login

You will be able to login to the workstation for up to two weeks after your day at the lab. This way you can use matlab especially, since this is at the time of writing not available in the CIP-pool.

Instruction 11 Remote Connection

To connect you either have to work from the university network MWN or gain access to it via VPN. The LRZ, the institute providing network services for all universities in Munich, has a comprehensible guide on how to establish the VPN for different OS:
https://www.lrz.de/services/netz/mobil/vpn/
When you are within the MWN, the next step depends on your operating system.

For Linux:
1. Open a terminal and enter
2. "xfreerdp -f -d AD gar-ex-medass02@garching.physik.uni-muenchen.de",
3.When asked for your user name use the login credentials you could find in the laboratory.
4.Leaving full-screen is done by pressing Alt +Ctrl +Enter .

For Windows:
1.Use the program "Connect to Remote Computer" / "Remotedesktopverbindung" provided by Windows since Win7,
2.The host to connect to is "gar-ex-medass02@garching.physik.uni-muenchen.de",
3.Use the login credentials you could find in the laboratory with the user name preceded by "AD\" to log in to the domain AD,
4.Leaving full-screen is done by pressing Alt +Ctrl +Enter .

6.2. Report

This is the final part of your work. You're supposed to write a comprehensive report of both the day in the lab and your results. Briefly describe the experiments, work out differences between the two dosimetry systems and compare the Optidos measurements to the simulations. Include proper error-estimations as well.

6.2.1. EBT3-FIlms

Please answer the following questions and include meaningful figures!

6.2.2. Optidos

6.2.3. Comparison to FLUKA

Since the simulation was set up to resemble the Optidos-measurements, figure out how to compare their respective results to each other. Your focus should be any discrepancies between real and simulated measurement. How big are they and can you give explanations for them?

Question 7: Tasks for Film Analysis

1. Judging by your first analysis of the films, is EBT3 a precise measurement device for absolute dosimetry?
2. Apart from mean dose values, what other information could you find during that analysis (Profiles!)?
3. Perform another analysis with a different ROI. Try to obtain as precise a depth dose curve as possible!
4. Can you directly compare Optidos measurements to those performed with the films?

Question 8: Tasks for Optidos Analysis

- Visualize the data (1D with error bars and 2D) and verify the $\frac{1}{r^2}$ range-dependency.
- If the 2D-scans are not symmetric explain that!
- How far-off was your estimate of the center of the source?
- Compare the characteristics of EBT3-FIlm measurements to those with Optidos! Work out advantages and disadvantages in both methods.

Appendix A.

Inventory

A.1. General

- Workstation with EPSON 11000XL scanner[1] connected**??**, running WINDOWS

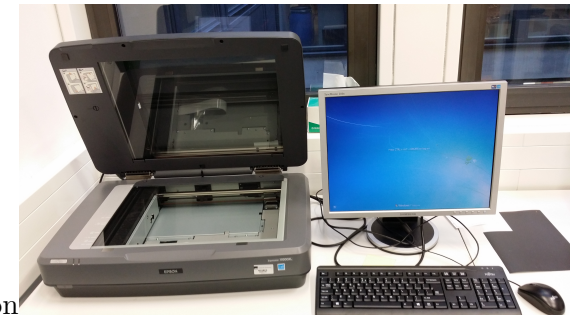


Figure A.1.: Scanning Workstation

- Workstation with Optidos^{TM} and motor stage connected, running Windows.
- Water phantom

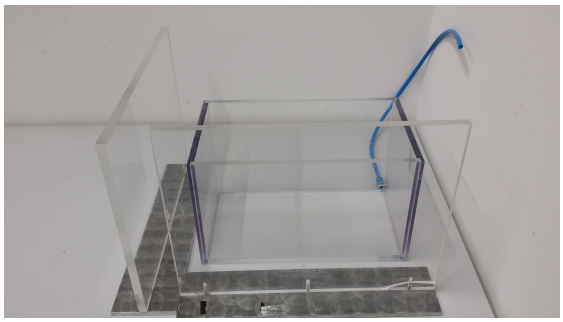


Figure A.2.: Water Phantom

- 2 acrylic walls
- Safe containing 2 beta-ray-sources of strontium-90 in their respective container

[1] please be very careful with it! The cost of this piece of hardware is in excess of 1500€

A.2. Gafchromic Films

- Sheet of gafchromic EBT-3-film, approximately 10 \cdot 12cm
- Scissors
- Marker pen
- Ruler
- Nitril gloves
- Box of Tissues
- Bottle of isopropyl alcohol
- Microfibre cloth
- Manual Scanning gafchromic filmsC

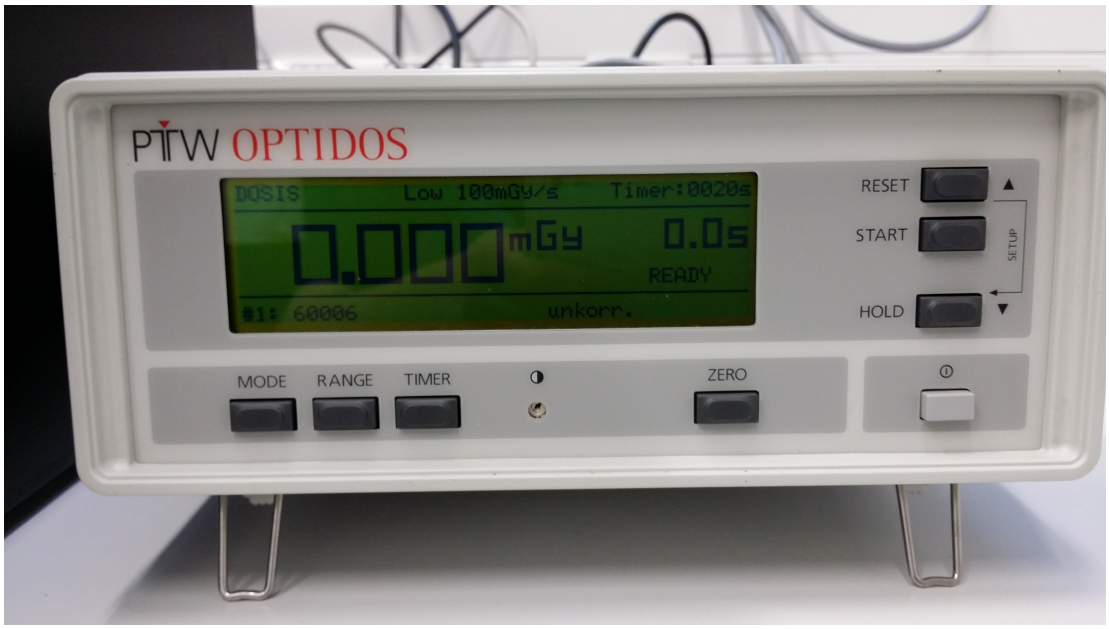
A.3. Optidos™

- OPTIDOS-device
- Serial RS-232-Cable for connection to the Workstation (already installed)
- Optical fibre with scintillation detector attached
- "Kontrolladapter"
- 3-axis motor-stage (already connected to the workstation)
- Jerrycan of purified water (5l)
- Detector-mount
- Source-mount
- 2 screw drivers
- Several screws

Figure A.3.: Strontium90-source BL 730 in container mark 8921, view from top

Figure A.4.: Strontium-90-source BL 730 in container mark 8921

Figure A.5.: OPTIDOS-device



Appendix B.

Listings

List of Questions

List of Instructions

List of Algorithms

Appendix C.

Scanprotocol

Scanning gafchromic Films (Epson Expression 11000 XL Pro)

Orientation: see backside for visual guidance

Landscape (preferred)
the long side of the original film (the one you cut your pieces from) is perpendicular to the scanning direction

Portrait (use is discouraged)
the long side is parallel to the scanning direction

Marking:

By convention we mark all films with an arrow pointing along the landscape-direction of the original uncut piece of film.
Since the layers of EBT-3-films are symmetric there's no difference which side of the film is up, but keep in mind that the older EBT-2-films are asymmetric!

Scanning:

Start the Epson Scan tool to aquire your scans.
Make sure „Modus“ / „Mode“ is set to *Professioneller Modus*.
To work in transmission mode choose „Vorlagenart“*:* *Film* and for the gafchromic films you need to set „Filmtyp“ to *Positivfilm*.

Now it's very important to deactivate any image corrections!
So you have to check if really all hooks are removed from the options, refer to the backside of this guide for how the mask should look now.

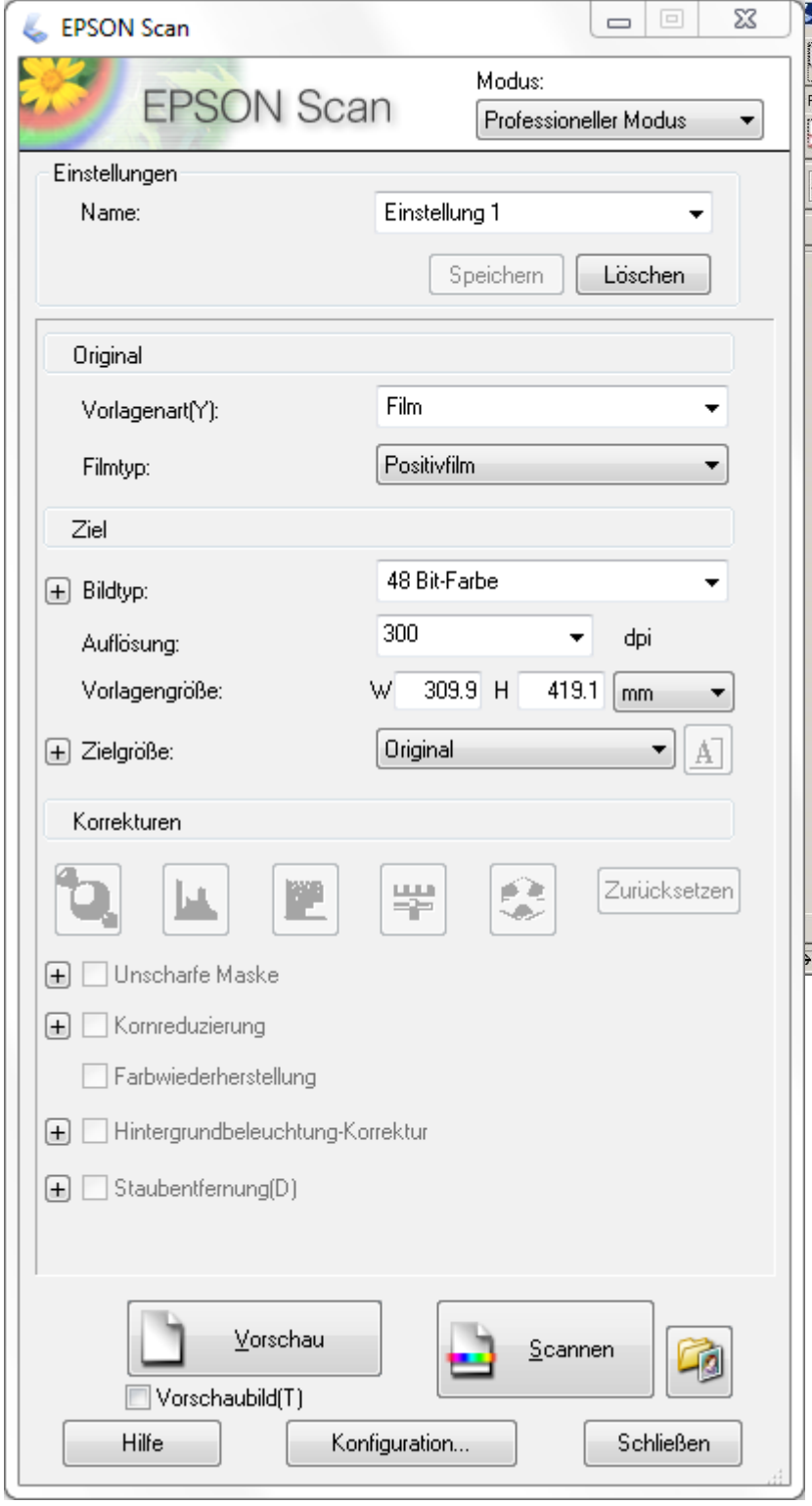
Finally make sure again that your films are aligned correctly (orientation-wise), all image corrections and the option below „Vorschau“ Vorschaubild(T) are deactivated and you have the following settings:

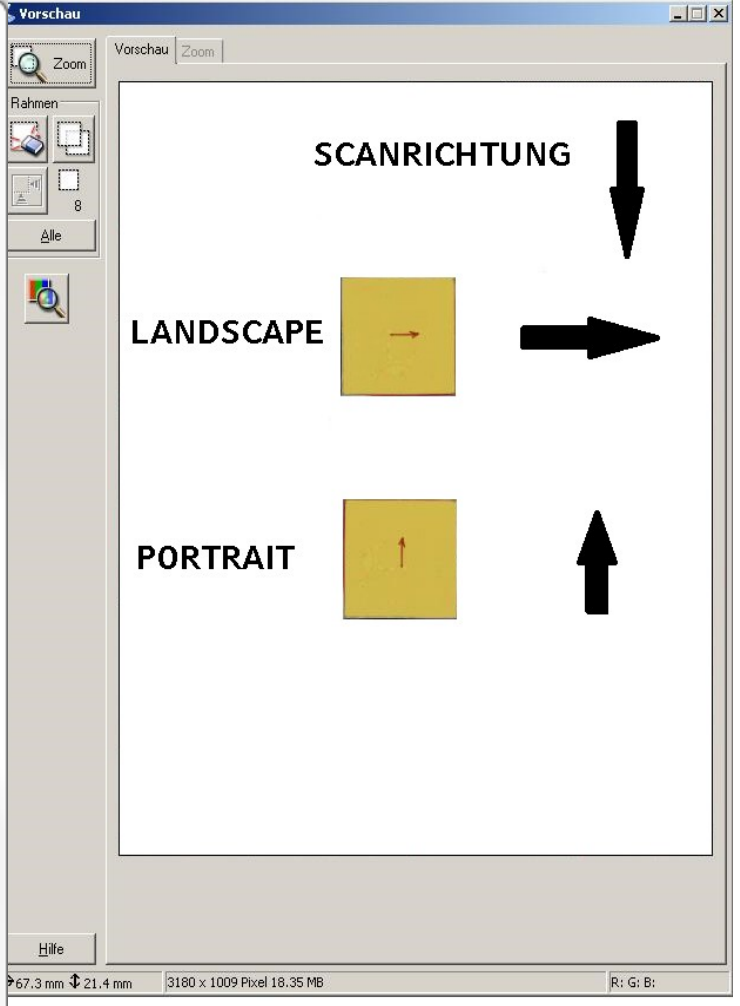
- Vorlagenart: Film
- Filmtyp: Positivfilm
- Auflösung: 72 dpi - 1200 dpi (depending on the desired spatial resolution)
- Bildtyp: 48 bit Farbe
- Korrekturen: AUS / OFF

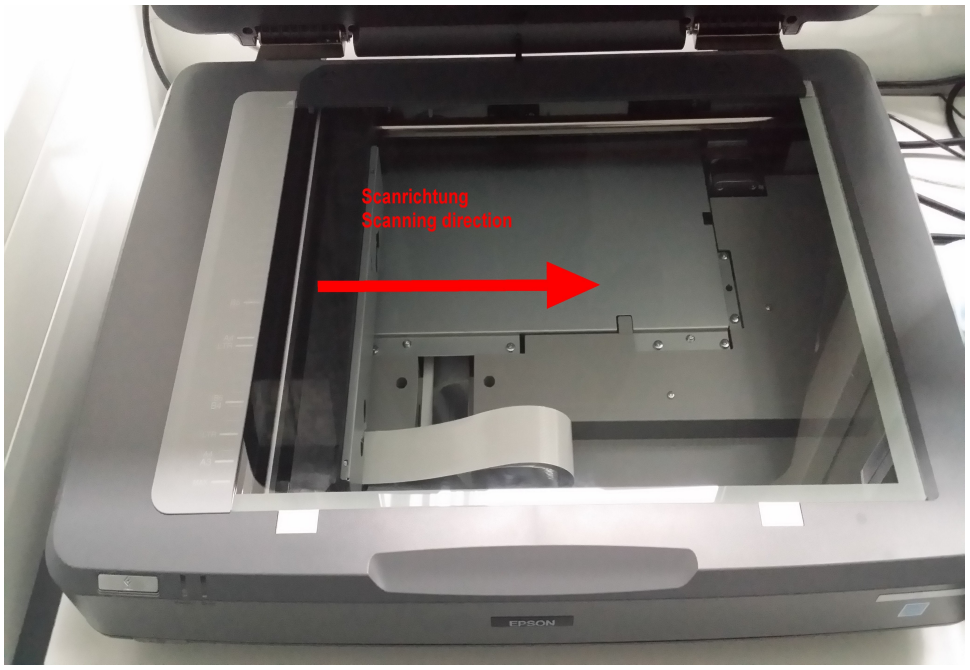
Now click the button „Vorschau“ / „Preview“. Then choose the area to be scanned and chose the following settings for saving the scans:

- Format: TIFF (*.tif)
- Byte-Folge: Windows
- Komprimierung: keine
- ICC – Profil: *Embed ICC Profile:* deaktiviert

Please note: Try to place your films in the middle of the scanning bed since
a)our calibrations usally are scanned there
b)to avoid the non-scanning-area of the device


EPSON Scan
EPSON Scan
Modus:
Professioneller Modus
Einstellungen
Name:
Einstellung 1
Speichern
Löschen
Original
Vorlagenart(Y):
Film
Filmtyp:
Positivfilm
Ziel
Bildtyp:
48 Bit-Farbe
Auflösung:
300
dpi
Vorlagengröße:
W 309.9 H 419.1
mm
Zielgröße:
Original
Korrekturen
Zurücksetzen
Unscharfe Maske
Kornreduzierung
Farbwiederherstellung
Hintergrundbeleuchtung-Korrektur
Staubentfernung(D)
Vorschau
Scannen
Vorschaubild(T)
Hilfe
Konfiguration...
Schließen


Vorschau
Zoom
Vorschau
Zoom
Rahmen
8
Alle
Hilfe
SCANRICHTUNG
LANDSCAPE
PORTRAIT
67.3 mm 21.4 mm
3180 x 1009 Pixel 18.35 MB
R: G: B:


Scanrichtung
Scanning direction
EPSON

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[2] D Delacroix. *Radionuclide and radiation protection data handbook 2002*. Nuclear Technology Pub.

[3] Slobodan Devic, Jan Seuntjens, Edwin Sham, Ervin B. Podgorsak, C. Ross Schmidtlein, Assen S. Kirov, and Christopher G. Soares. Precise radiochromic film dosimetry using a flat-bed document scanner. 32(7):2245.

[4] Hanno Krieger. *Grundlagen der Strahlungsphysik und des Strahlenschutzes*. Vieweg+Teubner Verlag.