# F80/F81: Scintillators

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# 1 Introduction

This experiment is intended to introduce you to some of the measurement methods in particle and nuclear physics. The detectors used in the experiment are scintillators two different types: Organic and inorganic scintillators. You will do a measurement of the endpoint energy of a $\beta$-decay will and you will make a coincidence measurement to detect cosmic muons and determine the dependence between their rate and their angle of incidence.

Your performance in this experiment is evaluated according to the following five equally weighted aspects:

1. Prediscussion: Your understanding of the physics and general background related to the contents of this experiment, as it is communicated before or during the experiment.

2. Conduct: The process of carrying out the experiment

3. Protocol: Record the information that is necessary for reproducing all of your results or partial results.

4. Lab report: Summarize, quantify and explain what you have measured.

5. Critical assessing: Think about and judge your results (quantitatively whenever possible).

Use the time in the laboratory first and foremost to carry out the experiment. Detailed data analysis, i.e. everything beyond that which is necessary to judge the integrity of your results should be done after the experiment.

# 2 Theory

## 2.1 Radiation

### 2.1.1 $\gamma$ radiation

$\gamma$ radiation occurs mostly as consequence of a previous $\beta$- or $\alpha$- decay and the subsequent transition of an excited energy state of the nucleus into its ground state. The energy difference between the two energy states is emitted as $\gamma$- radiation. The theoretical $\gamma$-spectrum is a discrete spectrum (two-body decay).

### 2.1.2 $\beta$ radiation

The $\beta$-decay is a three-body decay. A neutron decays into a proton, an electron and an electron antineutrino.

$$n \rightarrow p + e^- + \bar{\nu}$$

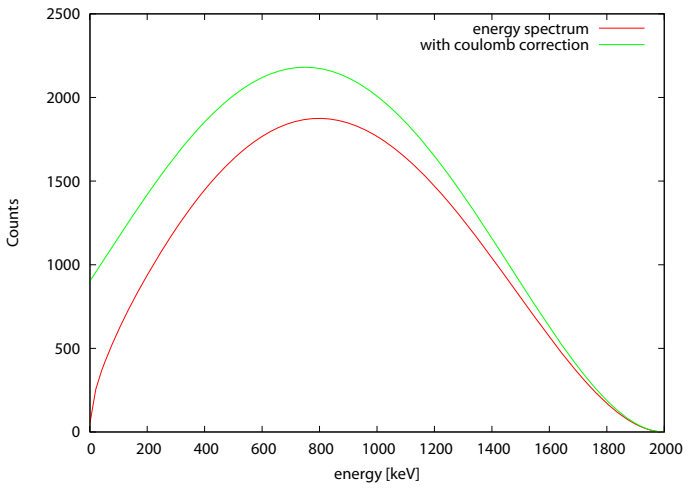


Figure 1: Theoretical $\beta$-spectrum of electrons with an endpoint energy of 2 MeV. In the green (red) curve, the effect of the coulomb potential of the nucleus on the $\beta$-particle are included (neglected).

The $\beta$- spectrum is continuous (Fig. 1) until the endpoint energy $E_{max}$, as it follows from Fermi's Golden Rule:

$$W = \frac{2\pi}{\hbar} \frac{dN}{dE_\beta} |H_{if}|^2$$

It follows for the counts per energy units:

$$\frac{\mathrm{d}N}{\mathrm{d}E_{kin}} \propto F(Z,E) \cdot (E_{kin} + m_e c^2) \cdot \sqrt{E_{kin}^2 + 2E_{kin} m_e c^2} \cdot (E_{max} - E_{kin})^2$$

(The deduction of this formula is to be found in the appendix.)
$F(Z,E)$ is the Fermi-Function. It is a correction factor to allow for the Coulomb interactions of the electrons with the nuclear charge, which slows down the emitted electrons and accelerates the emitted positrons. Therefore the Fermi-Function depends on the nuclear charge number as well as on type and energy of the emitted particles.

$$F(Z,E) = \frac{2\pi\eta}{1-e^{-2\pi\eta}}$$

In the case of $\beta^{\pm}$-decays $\eta = \mp\frac{Ze^2}{4\pi\epsilon_0\hbar c\beta_e} = \mp\frac{Z\alpha}{pc}$, here $\beta_e = \frac{p_e c}{E_e}$ is the velocity of the electron in units of c and $\alpha$ the fine-structure constant.

**Kurie-Plot** A graph with the variable

$$\sqrt{\frac{\frac{\mathrm{d}N}{\mathrm{d}E}}{F(Z,E)\cdot(E+mc^2)\cdot\sqrt{E^2+2Emc^2}}}$$

as function of the kinetic energy E is called Kurie-Plot. For allowed transitions it is a linear plot which crosses the energy axis in $E_{max}$, the maximal energy of the electrons. With this diagram we can extrapolate to maximal energy of our $\beta$-source quite accurately.

### 2.1.3 Cosmic muons

Muons are elementary particles, they are classified as leptons. Like electrons they have got a electric charge, but they are 207 times heavier than electrons ($m_e = 511\mathrm{keV}$) and unstable. Their mean lifetime is 2,19 $\mu$s.
Muons arriving on the Earth's surface are created indirectly as decay products of collisions of cosmic rays with particles of the Earth's atmosphere. Cosmic rays consists of high energy protons. These protons collide with molecules in the upper atmosphere they collide and pion and kaons are produced.

$$\begin{aligned} p + p &\rightarrow p + n + \pi^+ \\ p + n &\rightarrow p + p + \pi^- \\ p + p &\rightarrow p + \Lambda + K^+ \end{aligned}$$

Pions and kaons decay (amongst other decay channels) into muons.

$$\begin{aligned} \pi^+ &\rightarrow \mu^+ + \nu_\mu \\ \pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \\ K^+ &\rightarrow \mu^+ + \nu_\mu \end{aligned}$$

Only because they are highly relativistic, cosmic muons can reach Earth's surface before they decay. The rate of cosmic muons on sea level is of the order of $1\,\mathrm{cm}^{-2}\,\mathrm{min}^{-1}$. In dependency of the zenith angle ($\theta$) the cosmics have to pass different coat thicknesses of the atmosphere and are absorbed in different ways. Because of this effect the rate of the cosmic muons depends on $cos^2\theta$.

## 2.2 Interaction of particles with matter

### 2.2.1 Photons

The intensity reduction of electromagnetic radiation in matter is exponential. If photons with an intensity $I_0$ pass through a material with a mass absorption coefficient $\mu$ and thickness x, the intensity of the outgoing photons is given by

$$I(x) = I_0 e^{-\mu x} \qquad \text{with} \qquad \mu = \sigma \frac{N_A}{A} \rho$$

Here $\sigma$ is the cross section, $N_A$ Avogadro's number and A the molar mass of the material. There are three different types of photon interaction in matter: the photoelectric effect, the compton effect and pair production.

**Photoelectric Effect** At energies lower than 100 keV the photoelectric effect is dominant. If the energy of the photon $E_\gamma$ is higher than the binding energy $E_b$ of the electron, the photon can be absorbed by the electron. The outcome of this is a free electron with an energy of $E_e = E_\gamma - E_b$ and a hole in the atomic shell.
The cross section of the phototelectric effect depends on the atomic number Z and on the energy of the photon $E_\gamma$

$$\sigma_{pe} \propto \frac{Z^5}{E_\gamma^{7/2}}$$

**Compton effect** The Compton effect is the scattering of a photon with an electron. It is the dominant effect at energies of about 1 MeV to 2 MeV. During a Compton scattering process, the photon transfers a part of its energy and momentum to the electron.

Regardless of the details of the scattering process, we know that energy and momentum are conserved:

$$E_\gamma + E_e = E'_\gamma + E'_e \tag{1}$$
$$\boldsymbol{p}_\gamma + \boldsymbol{p}_e = \boldsymbol{p}'_\gamma + \boldsymbol{p}'_e \tag{2}$$

For sufficiently large $E_\gamma$ we can neglect the binding energy of the electron in the atom and thus consider the electron as free and in rest (Fig. 2):

$$E_\gamma + m_e c^2 = E'_\gamma + E'_e \tag{3}$$

$$\boldsymbol{p}_\gamma = \boldsymbol{p}'_\gamma + \boldsymbol{p}'_e \tag{4}$$

For each conservation law, an expression for the momentum of the scattered electron as function of the initial and final gamma Energy can be obtained. (Use the relativistic energy-momentum relation and the definition of the scalar product.) Equating the two expressions yields an expression for the change in the photon energy in a Compton scattering process:

$$\frac{1}{E'_\gamma} - \frac{1}{E_\gamma} = \frac{1}{m_e c^2}(1 - \cos\vartheta) \tag{5}$$

The energy transfered to the electron depends on the scattering angle $\vartheta$ and is maximal when the photon is backscattered ($\vartheta = 180°$). The maximum energy transfer in a Compton scattering process, the energy value $E_\mathrm{c}$ of the so called Compton edge, can be calculated: Using (5) we can obtain an expression for $E_{e'} = E_\gamma - E_{\gamma'}$ as function of the initial photon energy $E_\gamma$ that we evaluate at $\vartheta = 180°$. The energy value of the Compton edge is:

$$E_\mathrm{c}(E_\gamma) = E_\gamma \left(1 - \frac{1}{1 + \frac{2E_\gamma}{m_e c^2}}\right) \tag{6}$$

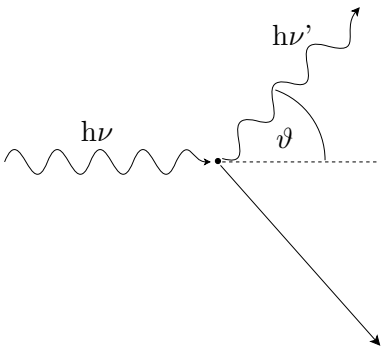


Figure 2: Kinematics of Compton scattering

The cross section of Compton scattering on atoms is proportional to Z:

$$\sigma_C^{atom} = Z \cdot \sigma_C^e$$

with $\sigma_C^e$ is the cross section of the Compton scattering per electron, which is given by the Klein-Nishina formula.

**Pair creation** If the energy of the photon is high enough pair creation can take place. The rest mass of two electrons and the backstroke energy at the nucleus is required, so the photon needs to exceed a threshold value of:

$$E_\gamma \geq 2m_e c^2 + 2\frac{m_e^2 c^2}{m_{nucleus}}$$

For high energies the cross section of pair creation is given by:

$$\sigma_{pair} = \frac{7A}{9N_A X_0}$$

where $X_0$ is the distance in which the energy is reduced to a fraction of 1/e. Pair creation dominates the energy loss of $\gamma$ radiation for energies from 5MeV and above.

For high energies of the incoming photon, electromagnetic showers can occur. They consist of electrons, positrons and photons which are produced by interactions with matter and have enough energy to start further interactions.

The total absorption coefficient is the sum of the coefficients of the single processes (Fig. 2.2.1).

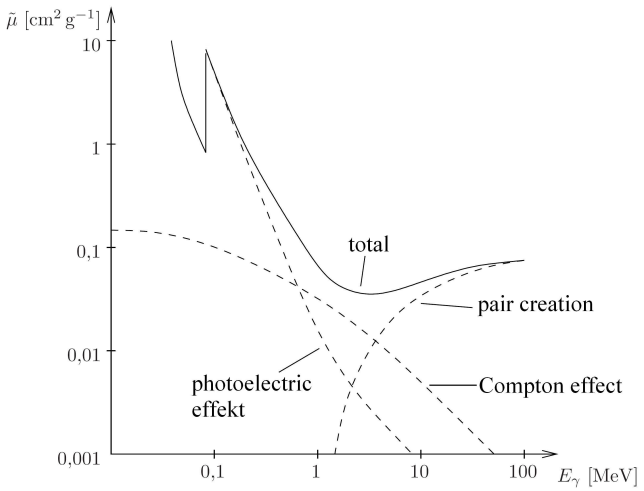


Figure 3: Total absorption coefficient for $\gamma$ radiation in lead

### 2.2.2 Charged particles

If charged particles traverse through matter, different processes of interaction can take place, such as ionisation, Bremsstrahlung, Cherenkov radiation or the particle can cause the emission of transition radiation.

**Ionisation** The Bethe-Bloch formula gives the energy loss by ionisation per distance for "heavy" particles:

$$-\frac{dE}{dx} = \frac{4\pi N_A r_e^2 m_e c^2 z^2 Z}{\beta^2 A}[ln(\frac{2m_e c^2 \beta^2}{(1-\beta^2)I}) - \beta^2]$$

where $z$ is the charge of the incoming particle in units of the elementary charge; $Z$ and $A$ the atomic number and the nuclear number of the absorption material; $m_e$ the electron mass; $r_e$ the classical electron radius; $N_A$ Avogadro's number and $I$ a material constant (approximately $I = 16Z^{0.9}eV$). The energy loss depends basically on the density of the material and is independent from the mass of the particle. Energy loss by ionisation is a statistical process, i.e. particles interact very often before they dissipate their whole energy. The Bethe-Bloch formula describes the mean energy loss.

**Cherenkov radiation** Cherenkov radiation occurs if the velocity of a charged particle passing through matter is higher than the velocity of light in the medium. The particle emits a characteristic electro-magnetic radiation. Atoms near the track are temporarily polarized, so they become electric dipoles and emit electromagnetic radiation because of the change in the dipole field in time.
The energy loss by Cherenkov radiation is given by:

$$\frac{1}{\rho}\frac{dE}{dx} \approx 0.5\frac{keVcm^2}{g}$$

Cherenkov radiation is useful for the detection of light particles.

**Bremsstrahlung** Fast charged particles loose energy by interaction with the coulomb field of nuclei of the medium. If the particles get slowed down in the coulomb field they loose their kinetic energy by emitting photons, this is the so called Bremsstrahlung. The energy loss by Bremsstrahlung is given by:

$$-\frac{dE}{dx} = 4\alpha \cdot N_A \frac{Z^2}{A} \cdot z^2 (\frac{1}{4\pi\epsilon_0}\frac{e^2}{mc^2}^2 \cdot E \cdot \ln\frac{183}{Z^{1/3}})$$

where $m$ is the mass of the particle.

Bremsstrahlung is only relevant for electrons. The energy loss for electrons is given by:

$$-\frac{dE}{dx} = \frac{E}{X_0}$$

For the ratio energy loss by Bremsstrahlung to energy loss by ionisation holds:

$$\frac{\frac{dE}{dx}_B}{\frac{dE}{dx}_I} = \frac{ZE[MeV]}{580}$$

## 2.3 Scintillator detector

The scintillator is one of the most commonly used detectors in particle physics. It makes use of the fact that certain transparent materials emit photons when ionising particles traverse them. The number of photons emitted is proportional to the energy loss by ionisation of the charged particle.
There are two different types of scintillators: the inorganic crystal scintillator and the organic scintillator ("plastic scintillator"), both of them will be used in this experiment.

### 2.3.1 Inorganic Scintillators

Inorganic scintillators are mostly used for energy measurements. They are ionic crystals doped with activator centers. The material used in our experiment is NaI(TI), a Natrium-Iodid crystals with a Thallium activator.
Typically, crystals are insulators: Their valence band is fully occupied but the conduction band is empty. The energy difference between the two bands is about 5 to 10 eV. Traversing charged particles lift electrons from the valence band into the conduction band, creating an electron-hole-pair, and both, the electron and the hole, can move freely and independently (Fig. 4). If the transfered energy is not sufficient for the electron to reach the conduction band, a so called "exciton" is created, a state in which the electron remains bound to the hole. Electrons, holes and excitons will diffuse through the crystal, until they reach an activator center. Activator centers introduce additional energy levels in between the valence and conduction band, where electrons, holes or excitons can convert their energy into photons for which the crystal is transparent (i.e. with energies lower than the band gap).
The time resolution of inorganic scintillators is impaired by the slow diffusion process by electrons and holes that access long-lived metastable states of the activator centers. On the other hand, the high atomic number of materials used for inorganic scintillators is beneficial for the detection probability. The large amount of scintillation light that is produced in inorganic scintillators causes the superior energy resolution.

### 2.3.2 Organic Scintillators

The most distinguishing feature of organic scintillators is a very rapid decay time. Because of this fact, they are ideal for time measurements. Organic scintillators can be fluid or plastic scintillators, so they can easily be produced in nearly every geometry.
The production of photons in plastic scintillators is a molecular process. A fluorescent substance is activated by the energy loss of a particle. At

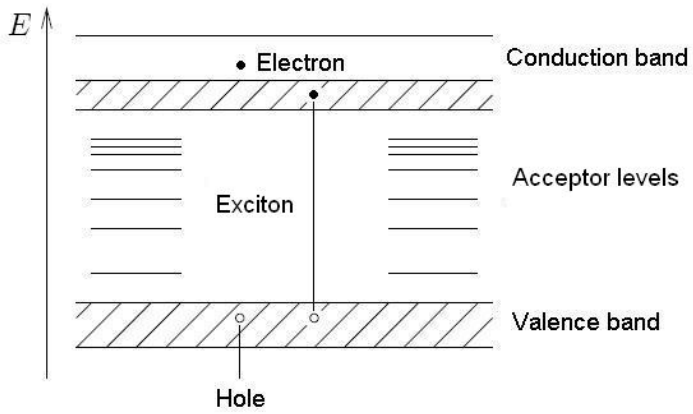


Figure 4: Energy band in inorganic scintillating crystals

the passage from the excited state to the ground state, ultra-violet light is emitted. Because the substance is not transparent for its own light, a second substance is added. This so called wavelength shift absorbs the emitted ultra-violet light and re-emits it again in a wavelength which can be detected by a photomultiplier.

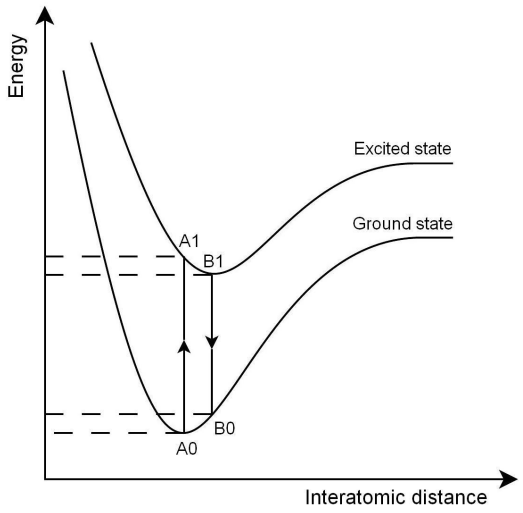


Figure 5: Energy band in organic scintillators

### 2.3.3 Lightguides

The light produced in a scintillator is transmitted to the photomultiplier by a lightguide. These are objects that are transparent for the scintillating light, shaped such that

- the form of the scintillator is converted to fit the photomultiplier tube
- photons from the scintillator experience only total reflection on the lightguide boundary

### 2.3.4 Photomultiplier

The instruments used for detecting fast light signals are photomultipliers. Electrons are emitted from an alkalimetal-photocathode by photo electric effect from visible light coming from a scintillation counter. These electrons are accelerated by an electric field to the first dynode (Fig. 2.3.4), which is part of a multiplying system.

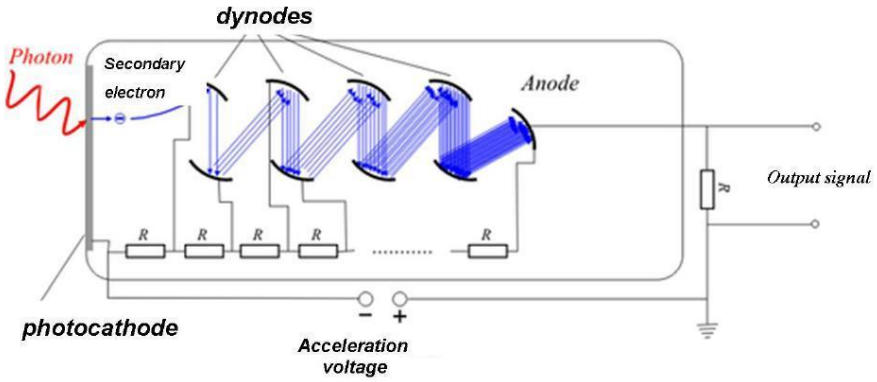


Figure 6: Photomultiplier

The amplification factor of a photomultiplier depends on the number of dynodes in the multiplier and the secondary emission factor $\delta$, which is a function of the energy of the primary electron. The energy of the electrons on each dynode is a function of the potential difference V between the dynodes. If N is the number of stages in the photomultiplier and K is a proportionality constant we can write for the gain G:

$$G = \delta^N = (KV)^N$$

## 2.4 Coincidence measurements

The coincidence method is a well established technique in nuclear physics to gain insight into details of a reaction or decay process. With this method, the simultaneous presence of two (or more) decay or reaction products can be verified. Because of the uncertainty inherent to all measurement processes, the decision if two signals are simultaneous is made in a time window of finite size, i.e. the coincidence measurement verifies that processes appear simultaneous only on a timescale larger than the so called coincidence resolution time. We will use the coincidence method to detect cosmic muons passing through two scintillators in a coincidence circuit.

### 2.4.1 Accidental coincidences

By making coincidence measurements we have to consider the possibility of "accidental coincidences" which can occur from uncorrelated background events in the detector: Two scintillators will register two *independent* signals separated by less than the coincidence resolution time just by chance, if we wait long enough.
The rate of accidental coincidences $R_{acc}$ can be calculated from the signal rates of the individual scintillators with the given formula:

$$R_{acc} = \sigma N_1 N_2$$

with the counting rates $N_1$ and $N_2$ of each scintillator on its own and the coincidence resolution time $\sigma$, for which two signals are considered as coincident.

# 3 The experiment

## 3.1 Sources used in the experiment

We use three different radioactive sources which are commonly used in nuclear and particle physics as "calibration sources" and for tests of paticle detectors.

### 3.1.1 $^{137}$Cs

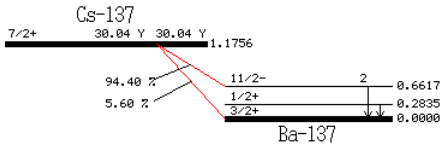


Figure 7: Decay scheme of $^{137}$Cs

Caesium 137

$E_e = 0.51397$ MeV
$E_\gamma = 0.66166$ MeV

half-life: 30.07yr

### 3.1.2 $^{60}$Co

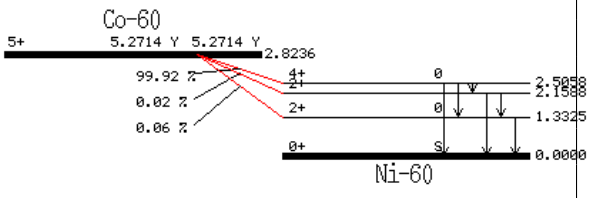


Figure 8: Decay scheme of $^{60}$Co

Cobalt 60

$E_e = 0.318$ MeV

$E_{\gamma 1} = 1.1733$ MeV
$E_{\gamma 2} = 1.3325$ MeV

half-life: 5.2714yr

### 3.1.3 $^{90}$Sr

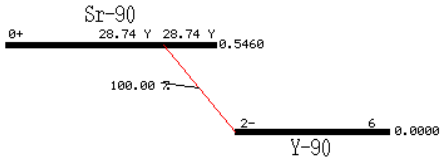


Figure 9: Decay scheme of $^{90}$Sr

| Strontium 90<br><br>$E_e = 0.5460$ MeV<br><br>half-life: 28.74yr |
|---|

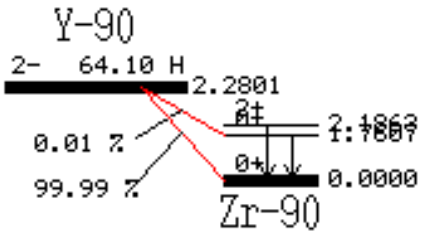


Figure 10: Decay scheme of $^{90}$Y

| Yttrium 90<br><br>$E_e = 2.2801$ MeV<br><br>half-life: 64.1h |
|---|

## 3.2 Equipment used in the experiment

### 3.2.1 High voltage

- Inorganic scintillators: Max. 450 V (positive polarity)
- Organic scintillators: Max. −2000 V (negative polarity)

### 3.2.2 Data taking software

You can analyse the scintillator data with a software written in LabVIEW via the following steps:

- The analog signal (that you can see on the oscilloscope) needs to be converted into digital information (a set of numbers) using an Analog-to-Digital Converter (ADC): Connect cable carrying the signal you want to record to the "ADC AIN +" of the Logic Box (the device labeled "TYPE: DL706_LP23")

- Check the USB connection from the Logic Box to the computer belonging to your experiment

- Start the LabVIEW software with the shortcut named "F80" on the desktop and change to the LabVIEW run mode ("Operate→Run")

- In order to record a spectrum, you first need to know the signal characteristics: Important is: The value of the baseline level and the relative position of the signal level.
  Go to the "Test ADC" panel, change the trigger from "Free Run" to "internal". The graph in this panel is like the graph of an oscilloscope and you can set the trigger level using the parameter "threshold" (in the top left of the panel), similar to the trigger function of an oscilloscope. When you have found a suitable trigger threshold value, close the "Test ADC" panel.

- Open the "Acquisition: Spectrum" panel, enter the threshold value that you determined in the previous step. Set the maximum measurement time (you can always abort the measurement early, if needed) and hit "START OK" (top left).

The combination of ADC and the data taking software is used as a multichannel analyzer (MCA): Pulses are sorted by pulse height from low to high, incrementing the bin (channel) of a histogram by one entry each time a pulse of corresponding height is registered.

You can save the recorder raw data with the following steps

- Create the folder "C:\fp80_data*GroupName*" with a *GroupName* of your choice.

- Enter your *GroupName* in the field "Group" of the "Acquisition: Spectrum" panel.

- Then you can enter a file name (which should include at least include the source name and measurement duration) and save the raw data with the "Acquisition: Spectrum" panel.

### 3.2.3 Discriminator

A discriminator produces a logical output pulse (i.e. the pulse height is fixed and does not contain information) when the pulse height of an input signal

is above a certain threshold. If the pulse height of the signal is to low no response is made, so low amplitude noise can be blocked out. The threshold value can be adjusted in the LabVIEW software (in units of mV - use the oscilloscope for reference!).
We use a leading edge discriminator. A disadvantage of this method is the so called "walk" which is illustrated in Figure 11, it means that output signals are dependent on the amplitude of the input pulses, but this is not significant if amplitudes are restricted to a small range.

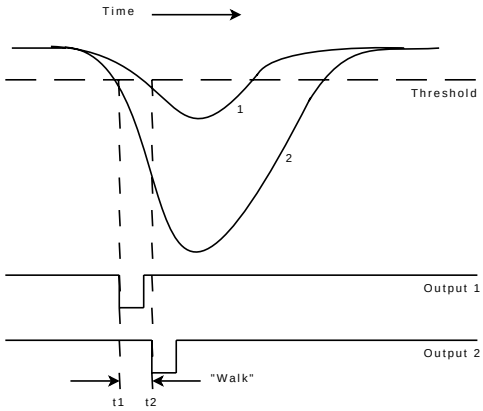


Figure 11: Leading edge discriminator

# 4 Energy measurements with the NaI scintillator

The goal of this experiment is to measure the maximum energy of the electron of a $\beta$ decay process of $^{90}$Sr and/or $^{90}$Y (page 17). Work with a NaI scintillator (the cylindrical detector) because their energy resolution is superior to organic scintillators. If available, use the NaI scintillator with the serial number "SAZ667".

## 4.1 Signal of the scintillator

Set up the experiment:

- Turn on the NIM crate (bottom right on the crate)
- With no connection on the HV power supply, turn it on an get familiar with the power supply: Set a voltage, choose positive polarity for the NaI scintillator.
- Set the HV to 0 V
- Connect the power cable and the signal cable.
- Gradually increase the HV to the desired value (max. 450 V for the PM of the NaI scintillator).

First, look at the signal of the inorganic scintillator with the oscilloscope. Use the oscilloscope's trigger to look for negative pulse signals of about 0.5 µs to 2 µs length and around 0.1 V to 1 V height. Make a sketch of the pulses, with time and pulse height information, into your logbooks.
Look at the signal with and without the $^{137}$Cs-source in front of the detector. (There is a plastic source holder, in which you can screw the staff sources to hold the source in place.)
Now use the amplifier on the scintillator signal before entering the oscilloscope and look at the signal with and without the $^{137}$Cs-source. Note your observations and interpretations.

## 4.2 Measuring and understanding the pulse height spectrum

The height of the scintillator pulses is proportional to the amount of energy deposited in the detector. A histogram filled with the pulse height information of the scintillator signal (the pulse height spectrum) yields a qualitative approximation of the energy spectrum of the source. (Qualitative due to lack of an energy calibration; approximative due to the binning.)
Use the setup for energy measurements (Fig. 12) to record a pulse height spectrum:

- Connect the NaI scintillator the amplifier input.

- Place the $^{137}$Cs-source in front of the detector
- Connect the amplifier output to the ADC input and record an energy spectrum of the source, as described in section 3.2.2.
- Try the various coarse gain settings of the amplifier and look at the spectrum (you have to delete the previously recorded spectrum with each new gain setting). Not all coarse gain values result in a meaningful spectrum. With very large coarse gain settings you can find out the highest usable ADC channel, determining the dynamic range of your setup. You will have to choose the amplifier settings according to the available dynamic range as well as on the maximum energy that you want to record. We will come back to this in 4.3.2.
- For now, adjust the amplifier gain such that most of the dynamic range of the ADC setup is used.

Explain the influence of the amplifier on the pulse height spectrum?
If you had no computer and no ADC but only the oscilloscope and pen and paper, how could you (in principle) produce the pulse height spectrum? (Of course this is not practical for a signal rate of some ten thousand per minute, so you will not do this. Only understand the principal procedure.)
Understand the spectrum of the source: From high to low energy (pulse height) values, the $^{137}$Cs source produces a single peak and a continuum. In the continuum of the $^{137}$Cs source, at least two structures can be identified (That is: You can calculate their position with only the information in this manual).

- Remind yourself: There are three processes in which photons interact with matter. What are the three?
- Due to which physical processes do you see the rightmost peak? To which energy value corresponds the peak position?
- Due to which physical processes do you see the continuum?
- Identify as many structures as you can and explain their origin.

## 4.3 Pulse height as function of voltage

In order to measure the average pulse height of the signal, record a pulse height spectrum as before. You know that the MCA sorts pulses by pulse height, so you can use the position of e.g. the photopeak as indicator for the pulse height.

1. Set the HV for the NaI scintillator PM to 450 V

2. Measure the pulse height with the photopeak position in the pulse height spectrum (in units of channels).

3. Repeat step 2 for 435 V, 420 V, 405 V, 380 V and 370 V.

4. Plot the pulse height as function of the PM voltage.

Of what shape is this curve? How can you interpret your results?

### 4.3.1 Choosing a working voltage

In order to choose an optimal working voltage, determine the energy resolution $\frac{\Delta E}{E}$ of the detector as a function of the high voltage and **for fixed $E$**. We have not yet made an energy calibration, i.e. we have no valid conversion between "channel number" and "energy".
As an estimator for $\Delta E$, use the full width at half maximum (FWHM) of the photopeak (in units of channels) and use the channel of the peak position for $E$:

1. Set the HV for the NaI scintillator to 450 V

2. Adjust the amplifier settings such that the $^{137}$Cs photopeak is well in the dynamic range of the ADC, e.g. the photopeak in channel 500.

3. Mark the peak position with the cursor in the LabVIEW software.

4. Measure $\frac{\Delta E}{E}$ for the $^{137}$Cs photopeak.

5. Repeat steps 2 to 4 for 440 V, 430 V, 420 V and 410 V. After changing the voltage, **adjust the amplification** such that the photopeak is reasonably close to the channel you used before in step 2!

6. Choose a working voltage from your results and keep it for the following measurements. (Changing the voltage influences the total gain, as does the gain setting on the amplifier and the following energy calibration is of course valid only for the very gain setting used during the calibration process!)

### 4.3.2 Energy calibration

Before we can do a quantitative measurement of the $\beta$ spectrum we have to calibrate the detector setup, i.e. find the relationship between channel number and energy.
You know the energy of the photons of the $^{137}$Cs decay (Fig. 7, page 16) and $^{60}$Co decay (Fig. 8, page 16) and you can identify the structures tied to the photoelectric effect in the pulse height spectrum.
Before you use this information to make the energy calibration, go through the following steps:

- Remind yourself (or verify with a measurement) that the dynamic range of the ADC is limited.
- Ask yourself: What is the highest energy that the setup should be able to measure? (Fig. 10)
- Ask yourself: How to ensure that this is still in the dynamic range?

Then

- Measure the pulse height spectrum of the $^{60}$Co source and adjust the amplification such that the photopeak of $\gamma_2$ (Fig. 8) is located in the middle of the ADC dynamic range (e.g. around channel 500 for an ADC with 1024 working channels).
- When you have found a suitable gain setting, record the $^{60}$Co that you will use for the energy calibration.
- Keep the amplifiers gain setting for the rest of the experiment.
- Record the $^{137}$Cs pulse height spectrum.
- Do a linear fit to find the relation between channel number and energy for your setup.

### 4.3.3 Determination of the end-point energy via Kurie-plot

Record the energy spectrum of the $^{90}$Sr source and compare it with the theoretical $\beta$-spectrum (Fig. 1, page 5). Where does the peak in the low energy levels come from?
Remind yourself that what you see here is the energy deposited in the detector, by an electron coming directly from the $\beta$-decay. In contrast, what you have seen before (the energy spectra of $^{60}$Co and $^{137}$Cs) is the energy that was deposited in the detector by an electron that obtained its energy from a $\gamma$-decay photon.[1]

In addition, you have additional effects that contribute to this pulse height spectrum. Remind yourself of effects of charged particles with matter: What is disturbing your measurement?

**Correcting the background** Not all events registered by the detector are due to primary electrons from one of the two $\beta$ decay processes of the source. Remind yourself of the possible interaction processes for charged

[1] The electrons from the $\beta$-decay of $^{60}$Co and $^{137}$Cs of course make contributions to the respective energy spectra as well. In addition, photons after a Compton scattering event might undergo secondary processes that contribute to the spectrum.

particles with matter. What background sources come to your mind?

Typical $\beta$ radiation is easily shielded by a few centimetres of material (low atomic number, to minimize hard bremsstrahlung). Thus, you can easily measure a good approximation of the background spectrum by shielding the primary electrons. For this purpose an acrylic glass plate is provided (chemically, acrylic glass consists of carbon, oxygen and hydrogen - low atomic number).

- Set up a background measurement, i.e. place the $^{90}$Sr and the acrylic glass plate into their respective holders and align them with the detector. (Be sure to orient the holder for the acrylic glass in the right direction. One end fits the NaI scintillator, the other end fits the source holder!)
- Remove the acrylic glass and record a spectrum of the $^{90}$Sr source. Choose a suitable measurement time. (Long enough for adequate statistics, but keeping in mind that you will have to execute this measurement about six times in total.
- Ideally, you make sure that you do not move the setup at all, until you have finished all $^{90}$Sr measurements completely. (Why is that?)
- Record the background spectrum, by placing the acrylic glass in between source and detector. (Same measurement duration)
- Use the LabVIEW software panel "data processing" to subtract the background spectrum from the recorder $^{90}$Sr spectrum. Save the background-corrected spectrum.
- Use the corrected spectrum to produce a Kurie-Plot and find out the endpoint energy of the electron of either the electron from the $^{90}$Sr (if visible in your measurement) or $^{90}$Y decay.
  At `www.physi.uni-heidelberg.de/Einrichtungen/FP/Auswertung/F80-81/` you can find routines and explanations for producing the Kurie-Plot.

Why differs the measured value so much from the literature value? To answer that question consult the sketch of the scintillator given in figure 18 in the appendix.

How can you correct for this using the given additives? Determine the corrected endpoint energy by repeated measurements of the endpoint energy for which you introduce additional aluminium material between source and detector. In a plot of endpoint energy as function of Aluminium thickness, extrapolate towards zero total aluminium. Make four additional measurements, using as little material as possible.

At the end of the last day, clean up the experiment: Ramp down the high voltage, turn of the power supply, oscilloscope and the NIM crate power. Put back the used cables and adapters.

# 5 Coincidence measurements with the organic scintillator - Measurement of cosmic muons

The coincidence measurements are carried out with the organic scintillators (the long, flat detectors wrapped in scotch tape or aluminium foil) because of their superior time resolution, compared to the NaI scintillator.

### 5.0.1 Signal of the organic scintillator

Set up the experiment:

- Turn on the NIM crate (bottom right on the crate)
- With no connection on the HV power supply, turn it on an get familiar with the power supply: Set a voltage, choose negative polarity for the organic scintillator.
- Set the HV to 0 V
- Connect the power cable and the signal cable.
- Gradually increase the HV to a value between −1700 V and −2000 V (don't exceed −2000 V) for the PM of the organic scintillators.)

Use the oscilloscope to study the signals of the organic scintillators. With the oscilloscope's trigger to look for negative pulse signals of about 10 ns length and around 100 mV height. Describe the difference that you see when pointing a source on the scintillator. Check in this way, that both scintillators are capable of detecting radiation.

### 5.0.2 Comparison of the spectra

Use the setup in Fig. 13 to record an energy spectrum of the $^{137}$Cs source, as described in section 3.2.2 on page 17. Describe the spectrum and compare it with the spectrum of the $^{137}$Cs spectrum that you have recorded (or will record tomorrow) with the NaI scintillator. Describe and explain the reasons for the differences.

## 5.1 Time measurements / Coincidence measurements

Because of good time resolution, we use the organic scintillators for the time measurements. To increase the rate of cosmic muons use the long inorganic scintillators for the measurements. We will measure the rate of muons as a function of altitude (in a horizontal coordinate system), thus the (poor) energy resolution is irrelevant for this measurement.

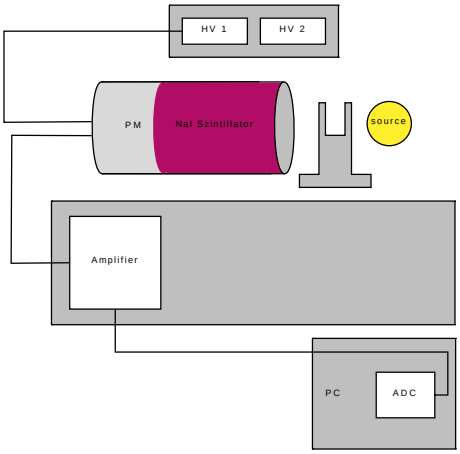


Figure 12: Setup for the energy measurements

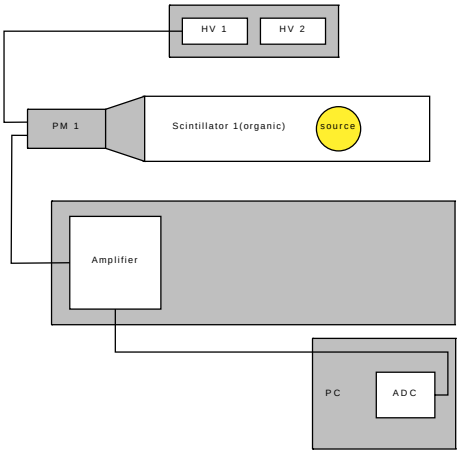


Figure 13: Setup with the organic scintillator

### 5.1.1 The Time Amplitude Converter / Time-to-Pulse-Height Converter

The information if two events are coincident or not is obtained with a time measurement using a Time to Amplitude Converter (TAC). This device has two inputs *start* and *stop* and one output. The device measures the time difference $\delta t$ between an arriving start and stop signal and produces a pulse with a pulse height proportional to $\delta t$. Recording this signal in a pulse height spectrum yields a time spectrum (in contrast to the energy spectrum, the horizontal axis of the time spectrum has the dimension of a time) with which truly coincident events can be distinguished from accidental (random) coincidences.

In order to get familiar with the coincidence measurement, make a measurement of cosmic muons:

- Place the two scintillators on top of each other.
- Set up the coincidence measurement (Fig. 14).
- Delay the stop signal by e.g. 32 ns. (A certain minimum of maybe 8 ns) is required.)
- If possible, use the NIM discriminator unit and verify the its function using the oscilloscope. If necessary you can vary the discriminator threshold using a screwdriver.
  Only if there is a problem with the NIM discriminator, use the discriminator of the Logic Box. In this case, open the LabVIEW software, go to the panel "Discriminator setup" and choose (for now) a discriminator threshold of the order of $-20$ mV to $-40$ mV.

- Record the pulse height spectrum of the TAC for a couple of minutes
- Place the two scintillators such that it is very unlikely for a muon to traverse both detectors and record a further pulse height spectrum.

At this stage you have to reach an understanding of this measurement deep enough to correctly answer the following questions:

- Describe and explain the spectra that you obtained via the previous two steps. How can you explain the difference?
- How can you distinguish random (background) from true (the muon signal) coincidences with this measurement?
- What is the effect of the delay time? (Very your ideas with a quick measurement!)
- Why is the delay used at all? (Think about what problems may arise with zero delay.)
- Why do you record the cosmic muons using a time spectrum (in contrast to e.g. an energy spectrum)?

### 5.1.2 Adjusting the threshold of the discriminator

In the leading edge discriminator a logic pulse (i.e. a pulse always of the same form, length and height, regardless of the input signal) is generated when the input signal exceeds an adjustable threshold value. Hence, the discriminator can be used to block low level noise. The threshold values that you choose will greatly affect the overall measurement rate and the rate of accidental coincidences. It should be adjusted as low as possible to maximize the detection efficiency of the scintillator, but there should be as little as possible noise.

Adjust the threshold such that the signal-to-background ratio is maximized:

- Set up the coincidence measurement (Fig. 14) and record the time spectrum for various discriminator threshold settings (Using a screwdriver, if you use the NIM hardware uni, or in the LabVIEW panel "discriminator setup", if you have to use the Logic Box' discriminator).
- In order to get a feeling for the threshold values you choose, compare the threshold level with the scintillators signal level (no amplifier) using the oscilloscope.

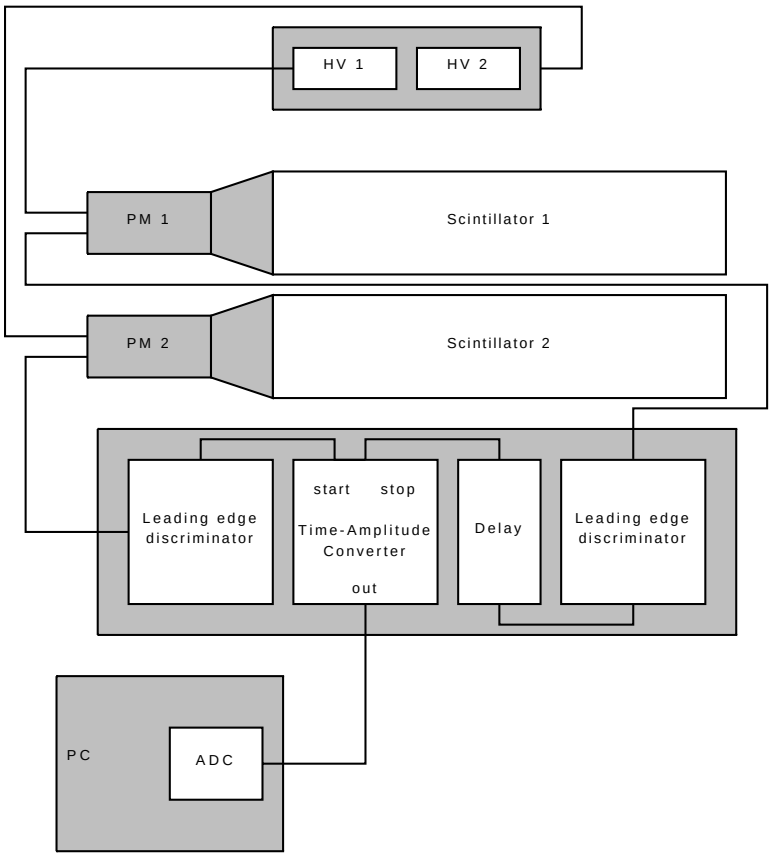


Figure 14: Setup for the time measurements. The two scintillators are supposed to be on top of each other, such that muons coming vertically downwards traverse both detectors.

- Count the entries $S$ of the signal (muons), count the number of entries $B$ of background events (random coincidences) and maximize $\frac{S}{S+B}$ as a function of the discriminator threshold values. (No detailed study necessary here. Spend about 10 to 15 minutes to find suitable discriminator thresholds).
  Use the integration markers of the LabVIEW software (bottom right) to count the events.

### 5.1.3 Working voltage of the organic scintillator

Still using the coincidence measurement setup (Fig. 14), maximize $\frac{S}{S+B}$ as function of the high voltage:

- Adjust the voltage for one of the scintillators to $-1500\,\mathrm{V}$ and keep this setting fixed.

- Record the pulse height spectrum of the TAC for with the second scintillator set to $-2000\,\mathrm{V}$, $-1850\,\mathrm{V}$, $-1700\,\mathrm{V}$ and $-1500\,\mathrm{V}$.
- Count the entries $S$ of the signal, count the number of entries $B$ of background events and maximize $\frac{S}{S+B}$ as a function of the voltage of the second scintillator.

### 5.1.4 Accidental coincidences

The background is uniformly distributed in the TAC pulse height spectrum, the signal is a peak on top of the uniform distribution. Thus, some background events are in the signal region. Calculate the background event rate using equation (2.4.1) on page 15 (for this you need to measure the signal rate of the discriminator signal). Estimate the background event rate by a direct measurement of the background rate.

### 5.1.5 Calibration of the time

Only with a time calibration of the pulse height spectrum (the relation between channel number and the time difference between start and stop in seconds) can you quantify the coincidence resolution time, the time resolution of your setup. Conceptionally you do the time calibration by introducing various known delay settings in the TAC pulse height spectrum and make a linear regression for the mean pulse height as a function of delay time.
The time calibration can be recorded quickly with the following steps (setup Fig. 15):

- Split the start signal on the TAC with a Y-adapter. Use one of the two signals as start for the TAC
- Delay the signal duplicate and use it as stop.
- Record a TAC pulse height spectrum and without interrupting the measurement, switch to several a new delay values.
- Keep record of which peak in the resulting spectrum belongs to which delay time.

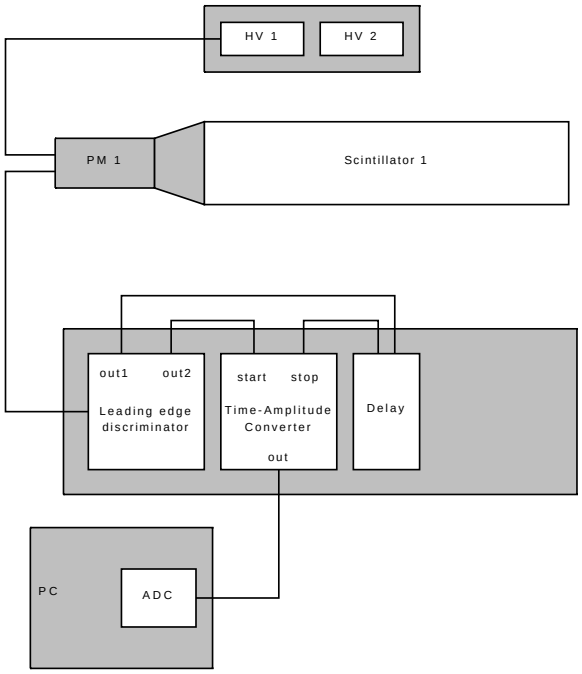


Figure 15: Setup for the time calibration

### 5.1.6 Scintillator orientation

For the coincidence measurement you can place the two scintillators on top of each other in a parallel or anti-parallel fashion (i.e. the two PMs on top of each other or the two PMs on opposite sides). One of the two possibilities is preferable.
Take a moment to think about the different situations. Try to think what happens (and what is different for parallel and anti-parallel scintillator placement) when you make coincidence measurements of cosmic muons.

And of course you will check your hypothesis with a measurement: Record a pulse height spectrum with parallel and with anti-parallel orientation of the scintillators.[2] Compare and interpret the results. Make a rough calculation to see if the effect can be explain by your hypothesis.

Calculate the time resolution of your setup (FWHM of the signal peak). From the previous measurement you can also determine the rate of cosmic muons per $m^2$s using the draft of the organic scintillator given in the appendix. Compare it to the literature value given in part 2.1.3.

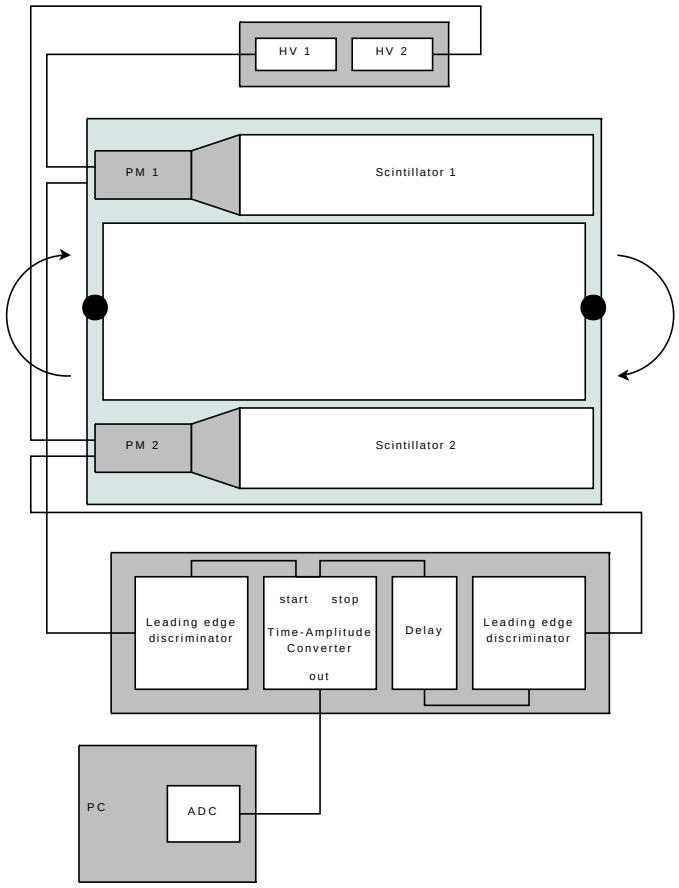


Figure 16: Setup for the measurement of cosmic muons

### 5.1.7 Cosmic muons

Put the scintillators into the rotatable steel instrument. Make measurements for every zenith angle $\theta$ $(0°, 22°, 45°, 67°, 90°)$ for 900s.
Make a plot of the counts against the angle of incidence and interpret your plot.
Fit a $cos^2(\theta)$-function to this data. At `www.physi.uni-heidelberg.de/Einrichtungen/FP/Auswertung/F80-81/` you can find routines and explanations that you can use for fitting. You should be able to explain, why the plot should be a $cos^2(\theta)$-function.
(You are asked to start your evaluation during this measurement!)

[2]The time resolution of the discriminators of the Logic Box is not good enough to measure the different scintillator alignments. You will only see the difference using the NIM discriminators. Hence, use these, if possible.

Clean up the experiment when you finished you are finished with the measurements: Ramp down the high voltage, turn of the power supply, oscilloscope and the NIM crate power. Put back the used cables and adapters and carefully remove the organic scintillators from the rotating metal frame.

# A Appendix

## A.1 The shape of the $\beta$-spectrum

The transition probability or decay rate per unit time is given by the following formula known as Fermi's Golden Rule:

$$W = \frac{4\pi^2}{h} \frac{dN}{dE_\beta} |H_{if}|^2 \tag{7}$$

Here $H_{if}$ is the matrix element between initial and final states, $E_\beta$ the energy in the final state and $\frac{dN}{dE_\beta}$ is the density of final states per unit energy interval. We only regard the $\beta$-spectrum of permitted transitions, in this case the matrix element is an erengy independent constant. Then the form of the spectrum is given by $\frac{dN}{dE_\beta}$.
We regard a phase space volume for electrons with an momentum between $p_e$ and $p_e + dp_e$ and for neutrinos with an momentum between $p_\nu$ and $p_\nu + dp_\nu$. The number of electrons in this phase space volume is:

$$dN_e = \tfrac{1}{h^3} \cdot V \cdot 4\pi \cdot p_e^2 dp_e$$

And the analog the number of neutrinos:

$$dN_\nu = \tfrac{1}{h^3} \cdot V \cdot 4\pi \cdot p_\nu dp_\nu$$

So we get the total number of states

$$dN = dN_e \cdot dN_\nu = (\tfrac{4\pi}{h^3})^2 \cdot V^2 \cdot p_e^2 dp_e \cdot p_\nu^2 dp_\nu$$

From

$$p^2c^2 = E^2 - m^2c^4$$

it follows that

$$pc^2 dp = E dE.$$

$$dN = (\frac{4\pi}{h^3c^2})^2 \cdot V^2 \cdot p_e \cdot E_e dE_e \cdot p_\nu \cdot E_\nu dE_\nu \tag{8}$$

Now we have to make two approximations: We neglect the backscattering energy of the daughter nucleus (this is possible because the mass of the nucleus is high against the mass of the electron and the neutrino), so

$$E_\beta = E_e + E_\nu$$

for $E_e$ energy (kinetic plus rest energy) of the electron and $E_\nu$ is the energy (kinetic plus rest energy) of the neutrino.

$$p_e^2c^2 = E_e^2 - m_e^2c^4 \qquad \text{and} \qquad p_\nu^2c^2 = E_\nu^2 - m_\nu^2c^4 = (E_\beta - E_e)^2 - m_\nu^2c^4$$

If we neglect the mass of the neutrino and insert in (2) it follows that

$$dN = (\tfrac{4\pi}{h^3c^3})^2 \cdot V^2 \cdot \sqrt{E_e^2 - m_e^2c^4} \cdot E_e dE_e \cdot (E_\beta - E_e)^2 \cdot dE_\beta$$

$$\tfrac{dN}{dE_\beta} = (\tfrac{4\pi}{h^3c^3})^2 \cdot V^2 \cdot \sqrt{E_e^2 - m_e^2c^4} \cdot E_e \cdot (E_\beta - E_e)^2 \cdot dE_e$$
$$\tfrac{dN}{dE_\beta} = K \cdot \sqrt{E_e^2 - m_e^2c^4} \cdot E_e \cdot (E_\beta - E_e)^2 \cdot dE_e$$

With the energy of the electron $E_e$ given by:

$$E_e = E_{kin} + E_0 = E_{kin} + m_ec^2$$

and the maximal energy of the $\beta$-spectrum is given by:

$$E_{max} = E_\beta - E_0$$

we get

$$\frac{dN}{dE_\beta} = K\sqrt{E_{kin}^2 + 2E_{kin}m_ec^2} \cdot (E_{kin} + m_ec^2) \cdot (E_{max} - E_{kin})^2 \cdot dE_e. \quad (9)$$

To allow for the Coulomb interactions of the electrons with the nuclear charge, which slows down the emitted electrons and accelerates the emitted positrons, we need a new correction factor the Fermi-Function, $F(E, Z)$. It depends on the nuclear charge number and the energy of emitted particles.

$$F(E, Z) = \tfrac{2\pi\eta}{1-e^{-2\pi\eta}}$$

In the case of $\beta^\pm$-decays $\eta = \mp\frac{Ze^2}{4\pi\epsilon_0\hbar c\beta_e} = \mp\frac{Z\alpha}{pc}$, here $\beta_e = \frac{p_ec}{E_e}$ is the velocity of the electron in units of c and $\alpha$ the fine-structure constant.

$$\frac{dN}{dE_\beta} = K \cdot F(E, Z)\sqrt{E_{kin}^2 + 2E_{kin}m_ec^2} \cdot (E_{kin} + m_ec^2) \cdot (E_{max} - E_{kin})^2 \cdot dE_e. \quad (10)$$

Now we can insert (3) in (1) and get the form of the $\beta$-spectrum:

$$W(E) = K^*\sqrt{E_{kin}^2 + 2E_{kin}m_ec^2}(E_{kin} + m_ec^2)(E_{max} - E_{kin})^2F(E, Z) \propto \underset{\frac{dN}{dE_{kin}}}{}$$

### A.1.1 Kurie- Plot

$$\sqrt{\frac{W(E_e)}{F(E,Z)\sqrt{E_{kin}^2+2E_{kin}m_ec^2}\cdot(E_{kin}+m_ec^2)}} = K \cdot (E_{max} - E_{kin})$$

If we plot the root gainst the kinetic energy $E_{kin}$ we get the Kurie-Plot. For allowed transitions it is a linear plot which crosses the energy axis in $E_{max}$, the maximal energy of the electrons.

## A.2 Plastic scintillator

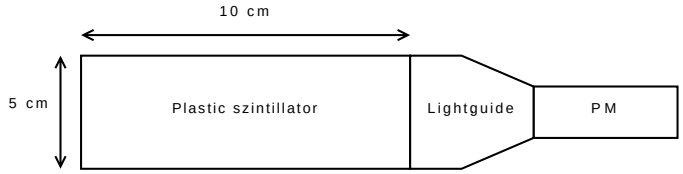


Figure 17: Platic szintillator

### A.3 NaI scintillator

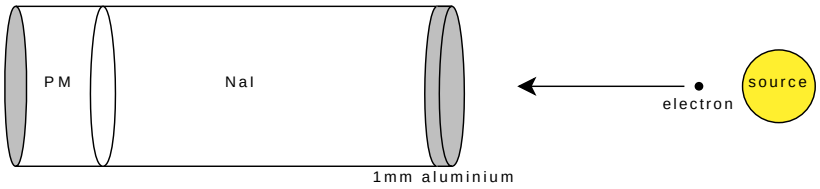


Figure 18: NaI scintillator

# B Further reading

## B.1 Exposure dose in the experiment

The activity of a source is the number of decays which can occur in a given time. It was historically measured in the unit Curie which are defined as:

$$1\,\mathrm{Ci} = 3.7 \times 10^{10}\,\mathrm{decays/s} = 3.7 \times 10^{10}\,\mathrm{Bq}$$

Curie is a very large unit, it was originally defined as the activity of one gram of Radium 226. One usually deals with sources which have activities in the order of µCi.

The radiation dose from ionising radiation absorbed from the body which comprises the effectivity of the radiation to the body is called equivalent dose. Its unit is Sievert (Sv). The sources we use in this experiment have low activity.

**Activity of the sources used in the experiment** (in a distance of 10cm):

$^{137}$Cs: 3.9 $\mu$Sv/h (33.3 mSv/a)
$^{60}$Co: 33 $\mu$Sv/h (282 mSv/a)
$^{90}$Sr: 0.42 $\mu$Sv/h (3.6 mSv/a)

**Exposure dose in the laboratory** For the measurement of the exposure dose a typical situation during the experiment was readjusted. One source was put in every setup, at the setup of of F81 the most powerful source of the experiment ($^{60}$Co) was used.

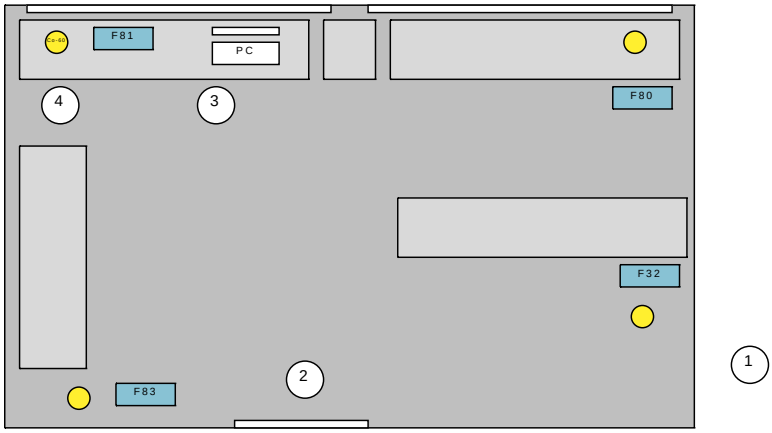


Figure 19: Exposure dose in the laboratory

Exposure dose at different positions (Fig. 19) in the laboratory:

1: 0.08 $\mu$Sv/h (0.70 mSv/a)
2: 0.09 $\mu$Sv/h (0.79 mSv/a)
3: 0.15 $\mu$Sv/h (1,3 mSv/a)
4: 4.00 $\mu$Sv/h (35 mSv/a)

For comparison, the natural exposure dose which is comprised of the cosmological radiation, terristric radiation and internal radiation averages 2.1 mSv/a.

However small amounts of radioactive sources in the body can be very harmful. The sources we use in this experiment are sealed and hence ingestion is impossible assuming their proper handling. Nevertheless one should always obey the following two rules when handling radioactive sources:

1. Never eat, drink or smoke in the laboratory!
2. Wash your hands after handling radioactive sources or lead!