Schüler Labor

GSI Helmholtzzentrum für Schwerionenforschung

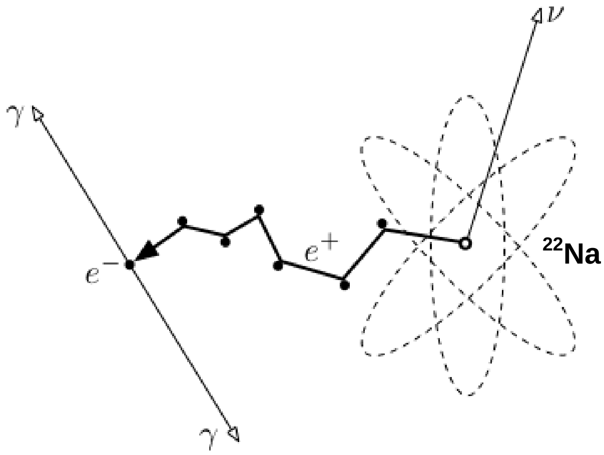
# Station 7

# $\gamma$-$\gamma$-Coincidence

# Content

# The Positron-Electron Annihilation radiation from Na-22

## What this is about

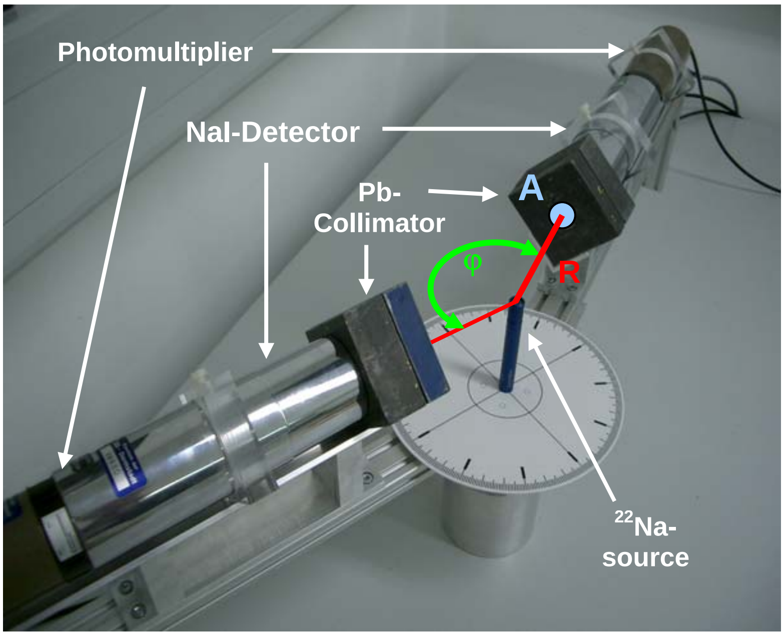



The radioactive nuclide Na-22 decays, by emitting an elementary particle called the positron (e+). This elementary particle is equal to the normal electron in all its properties, apart from the exact opposite charge. The positron has a positive electric charge! It is also called the anti-particle of the electron. The positron is therefore a bit of antimatter, which in our world made of matter, cannot exist for long. It is first slowed down in many collisions and then forms, together with an electron, a so-called positronium-atom, in which the electron and positron revolve around a common centre of mass. After several nanoseconds, the two anti-particles annihilate each other and in this process, their entire stationary mass is converted to radiation energy after the famous formula $E=mc^2$: From the place of annihilation, two gamma-photons are emitted in opposite directions, each one with energy of 511 keV.

This process is the basis of numerous interesting applications, for example in medical diagnostics in positron-electron tomography (PET). The following experiment is about demonstrating the special properties of the two coincident gamma-photons:
-Their exactly opposite direction
-Their speed of 300,000 km/s

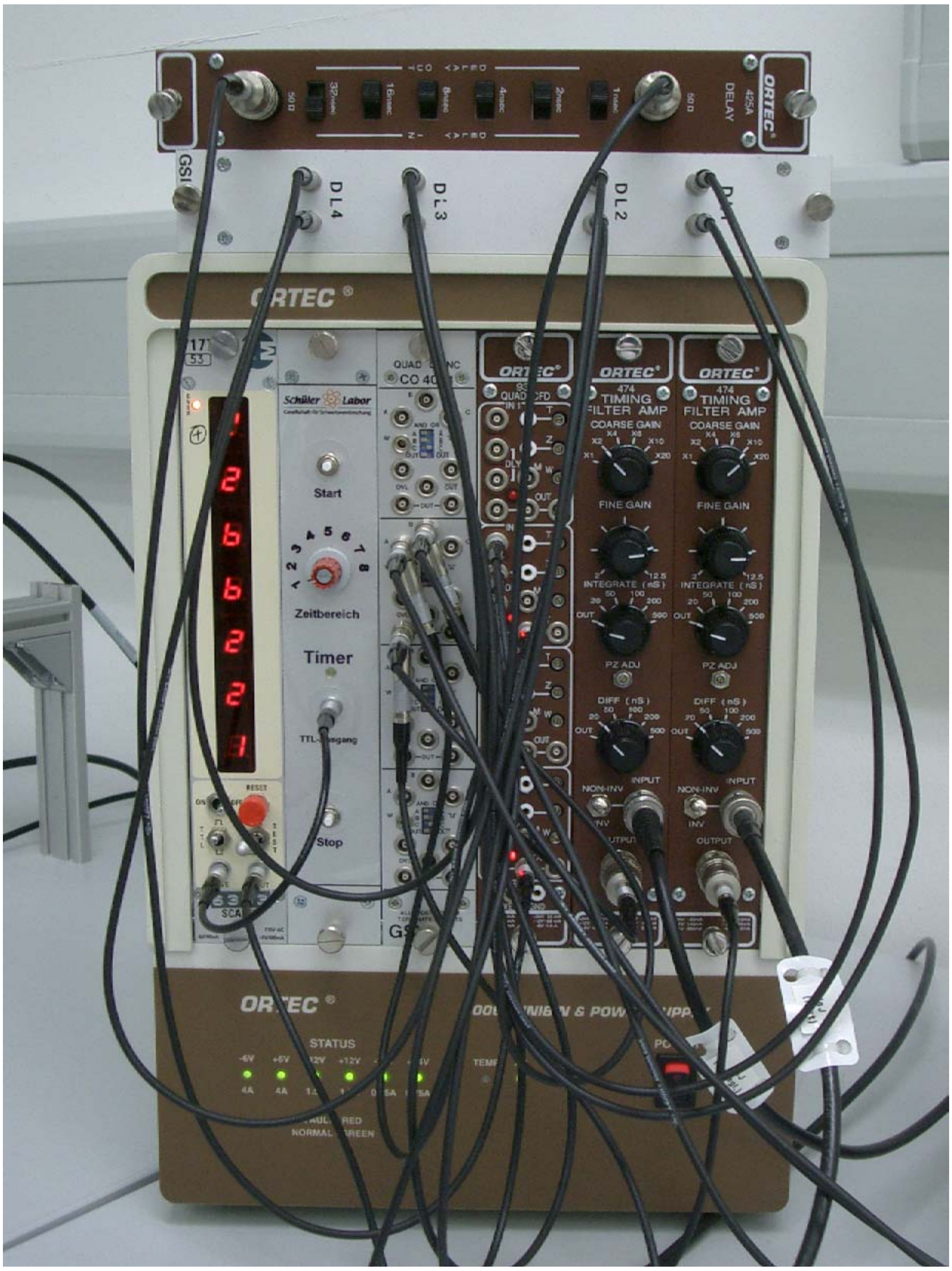
### *E.1. The experiment*

The figure shows the setup with two sodium-iodide detectors (NaI) with connected photomultipliers, of which the one at the back (right) is fixed and the one at the front (left) can be rotated parallel to the tabletop. Exactly in the rotational axis the mounting for the Na-22 source is found in the distance R to both detectors. The rotation angle φ between the two detectors can be set to within an accuracy of about ½ of a degree. In front of the two detectors, the gamma-radiation is limited to a circular surface A with two lead blinds (called Collimators).

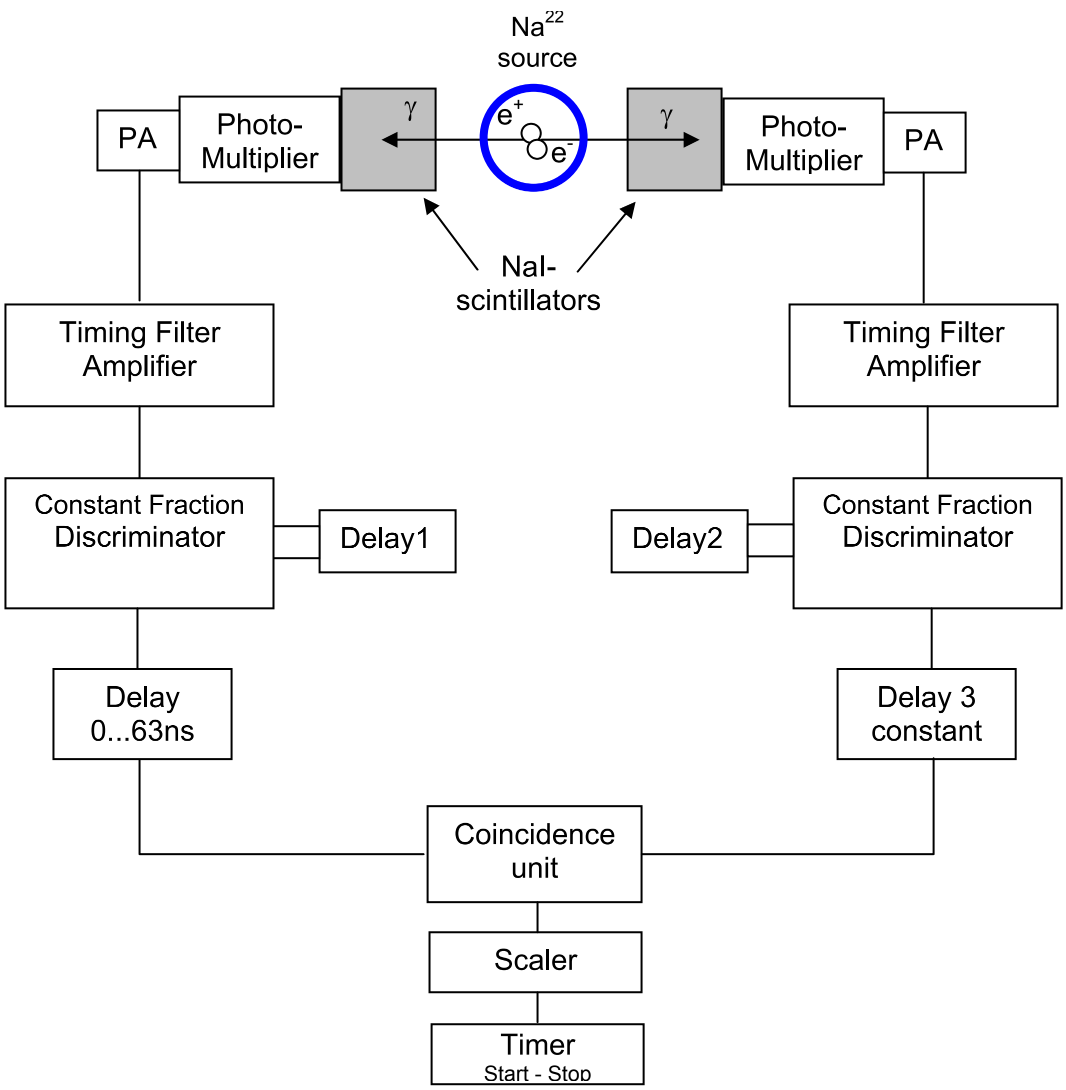


## E.2. Overview over the coincidence electronic

Both detectors are connected to a counting scaler via complex electronics. The scaler counts all gammas that are registered simultaneously within a certain time interval in both detectors. These electronics are placed in a frame called a mini-bin (see picture below). Shielded BNC-cables are used for supplying the bias voltage to the detectors and for taking the signal cables from the detectors. You also find thinner cables with smaller plugs, called LEMO-cables.




Since the cabling seems unclear on this picture, the entire setup of the electronics is shown again as a circuit diagram on the next page.



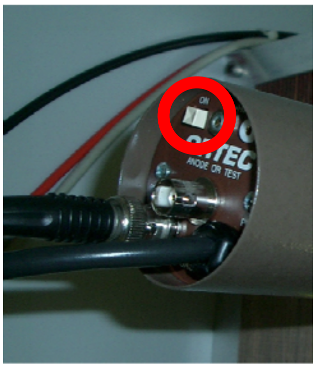

You can see that the diagram is symmetric and not that complicated. Each detector has a signal branch with the following components:

- A scintillator detector with a photomultiplier and a preamplifier (PA). These three components are placed together in the cylindrical detector housing.
- A main amplifier ("ORTEC 474 Timing Filter Amplifier", TFA)
- A constant fraction discriminator ("ORTEC 935 QUAD CFD) with a fixed delay (Delay and delay 2). The cable box lying on the mini-bin provides the fixed delay times with its four built-in extension cables
- A signal delay "Delay 3" (fixed, in the cable box) and "Delay 0…63ns" (adjustable in steps of 1ns)
- Both signal branches lead into a coincidence unit ("QUAD COINC CO 4001") with a connected timer and scaler.

☞ Trace all signal cables in the circuit diagram and find the named electronic modules in the mini-bin. Start with the two BNC-cables coming from the detectors (labelled "NaI (fixed)" and "NaI (movable)") and trace the signal cables to the scaler carefully and without pulling out any cable.

## E.3. Observation of the detector signals with the oscilloscope

### E.3.1. First steps




☞ Start up the electronics. For that purpose switch on the main switch (POWER) on the bin's bottom right. The LEDs should now light up.

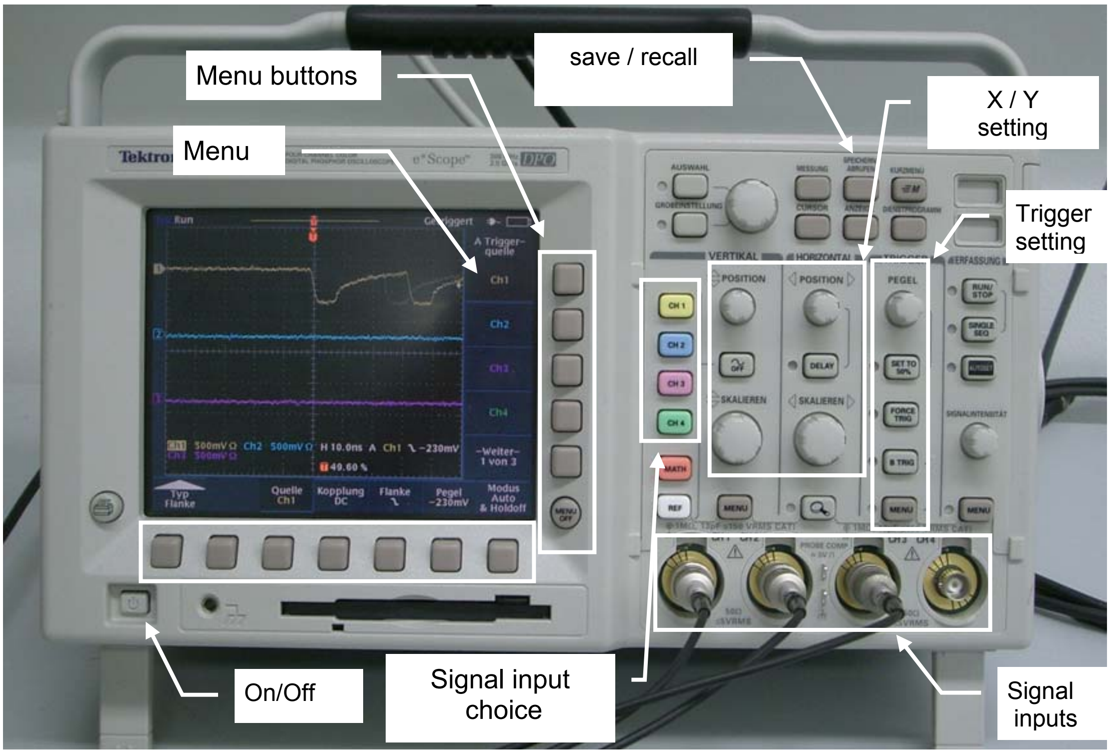
☞ Switch on the two NaI-detectors at the back of the photomultipliers' housings. A small rectangular switch to be pressed is located there (figure at the right).

After the switch-on, both detectors will already show signals as they are hit by gammas from the natural background radiation. Those signals should be inspected closer with the oscilloscope.

☞ Pull the BNC-plugs (labelled "NaI (fixed)" and "NaI (moveable)") from the input of the timing filter amplifier. These cables have a bayonet lock to protect them from unintended removal. The bayonet lock is opened by turning it to the left and closed by turning it to the right.

☞ Put the two plugs into the inputs labelled "Ch1" and "Ch2" of the oscilloscope (see figure below, any other cables possibly still connected should first be taken out)

A short introduction into the operation of an oscilloscope is found in the chapter on background knowledge, but the most important functions are shown in the following picture:




☞ Switch on the oscilloscope (bottom left button) and wait for the confirmation that all self tests have been successful.

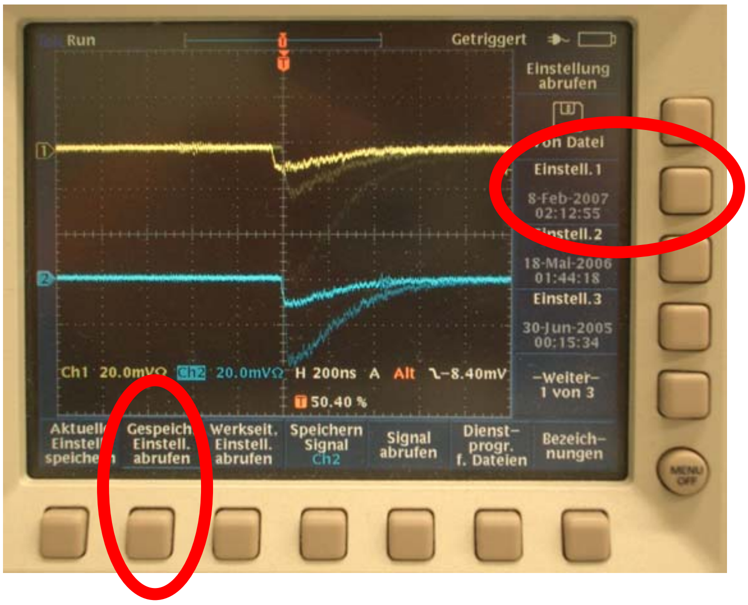
☞ To choose a pre-setting, press the “save/recall”-button (brown button at the top right). Afterwards you should see the menu as shown on the picture below.

☞ Press the menu buttons in the following order:

- “recall saved setting”
- “Setting 1”

☞ If this pre-setting has been overwritten, you can also re-call the oscilloscope setting from the 3.5’’ floppy disk en-closed in this manual:

- Press <from file>.
- Choose TEK00000.SET with the turning knob (above the word VERTICAL)
- Press <from chosen file>.




☞ In yellow [1] and blue [2] colour the signals of the two detectors will now be displayed. Even without a radioactive source, you should be seeing detector signals coming from the natural gamma-background radiation.

☞ What voltage do those signals have and how long do they approximately last? Estimate those values with the indicated scaling information: Ch1 20.0mVΩ means that for the signal input 1, 1 cm in y-direction corresponds to an electric signal voltage of 20mV (the Ω denotes that the input resistance of the oscilloscope is set to 50Ω). The indication H 200ns means, that in x-direction 1 cm corresponds to a time of 200ns.

☞ Observe the signals very closely in their temporal succession. How often can you observe two gammas arriving simultaneously in both detectors in one minute? Think and justify whether this is happening often or seldom.

Probably it was difficult for you to decide whether two detector signals happened exactly simultaneously or very shortly after one another. In the next section this is to be investigated more closely.

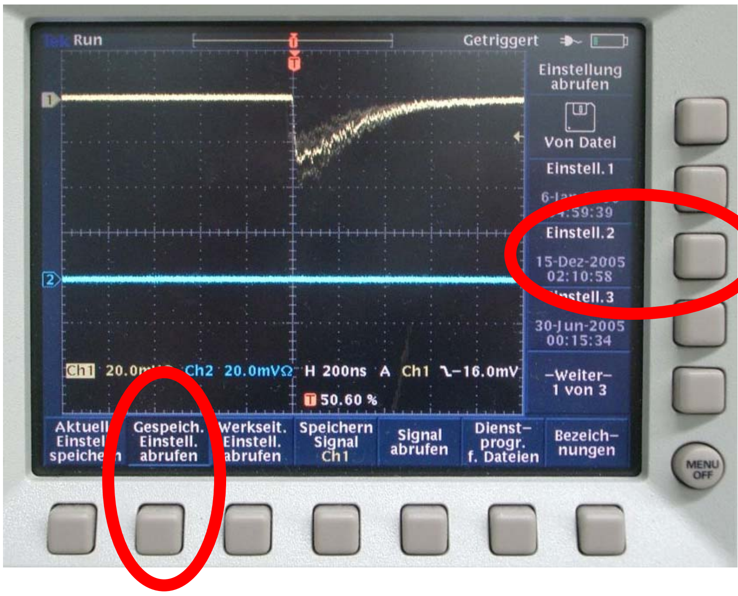
## E.3.2. Triggering

In the former section, the oscilloscope was set in such a way, that every electric signal that was registered in a signal input (1 or 2), was displayed on the screen. This shall be changed now.

☞ Recall (as described above), the pre-setting “setting 2”.

- Press the button “save/recall”
- Press the menu buttons in the order: - “recall saved setting” – “setting 2”

This example shows nicely what the word “trigger” means. It is often used in the context of technical, especially computer-based systems and denominates the start of a process after a certain event has happened. Let us assume as an example, that we have chosen Ch1 as a trigger source on the oscilloscope. Then the oscilloscope watches the voltage on the signal input 1 and only displays a signal on the screen, if the voltage has reached the trigger threshold. Like this it is assured that as good as every signal from Ch1 is also shown on the screen of the oscilloscope.




Check the effect of the following turning knobs (◊) and buttons(▯):

- o TRIGGER: THRESHOLD(◊) and MENU(▯)
- o VERTICAL: Ch1(▯) as well as Ch2(▯) and POSITION(◊) as well as SCALE(◊)
- o HORIZONTAL POSITION (◊) and SCALE (◊)

*If you got lost in the settings, you can always recall the basic setting as described above!*

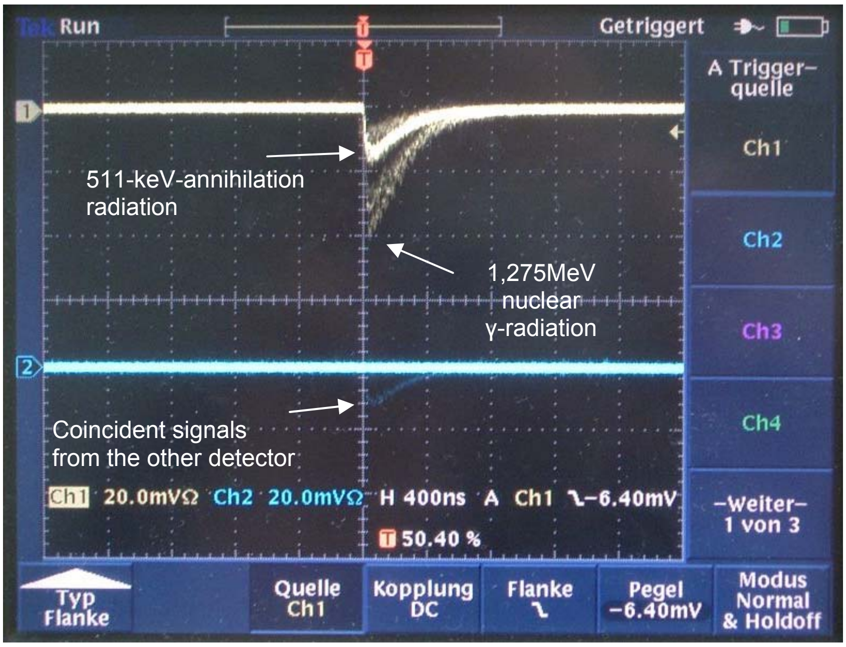
☞ Trigger now on Ch1 and put the beginning of the signal on the line in the middle (as shown in the picture above) with the knob HORIZONTAL POSITION. What time span before and after the beginning of the signal can you see with the setting H 200ns?

☞ ***Trigger alternatively on Ch1 and Ch2 and decide why, depending on the detector you trigger on, you can only see signals from the background radiation in one OR the other detector.***

### E.3.3. Coincidence

☞ Ask your supervisor to now to put the Na-22 source into the mounting and adjust the moveable detector to an angle of 180°!

You should now clearly see coincident signals from both detectors. You can also see that the source obviously emits two distinct gamma energies.




☞ By varying the trigger scale, show that only the lower energy 511-keV radiation is emitted coincidently and that the higher energy radiation (1.275 MeV) stemming from the atomic nucleus has nothing to do with this process.

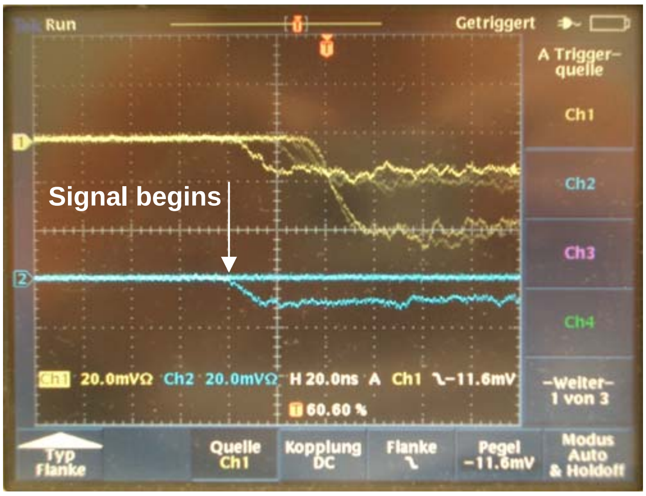
☞ With the oscilloscope, trigger alternatively on one or the other detector and estimate from the oscilloscope display how many coincidences you approximately get in one minute.

### E.3.4. Signal speed in cables

In many experiments at GSI, the electric signals cover a certain distance in cables and therefore get attenuated and delayed. You should now investigate this effect.

☞ Trigger on Ch1 and observe the beginning of the signal in Ch2 (possibly you'll need to use the horizontal-position-knob)

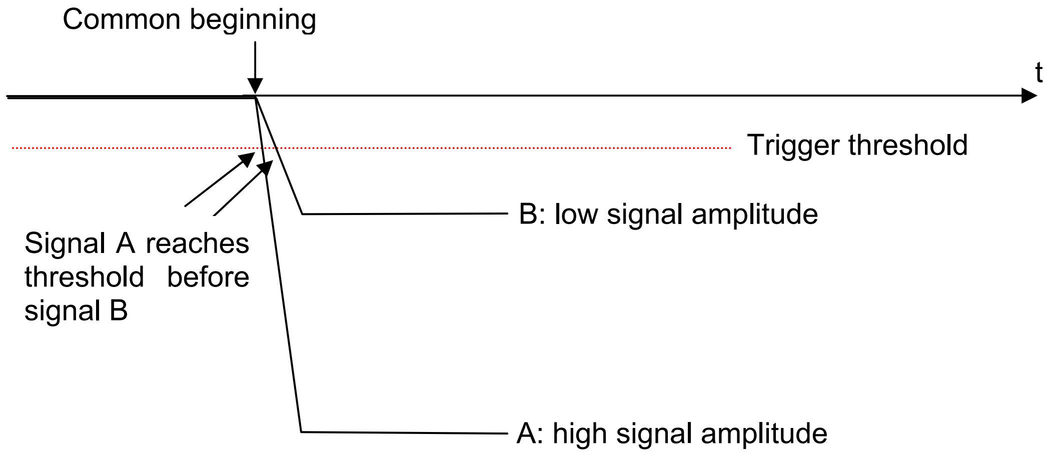
☞ Now extend the signal path for the signal in Ch2 with another BNC cable (measure the length!) and ascertain the delay of the beginning of the signal (in ns). To get useable results, change the horizontal scale to H 20.0ns.




From your results, calculate the signal speed in the cable in m/s and in percent of light speed (c=300,000 km/s).

## *E.4. The electronic processing of the detector signals*

The last task has shown you, that time measurements of the irregularly formed detector signals is rather difficult. You may also have noticed that the moment in which a signal crosses the trigger threshold depends on its amplitude: a large signal will reach the threshold earlier than a small signal.




With the signals as they come out of the preamplifiers it is difficult to show coincidences for the named reasons. Therefore the detector signals will be processed in further electronic modules before they can be used for the determination of a coincidence.

### E.4.1. The main amplifier (Timing Filter Amplifier TFA)


The preamplifiers placed in the photomultiplier housings serve to amplify the weak detector signals and to drive them through a cable to the main amplifier.

The main amplifier has two tasks:

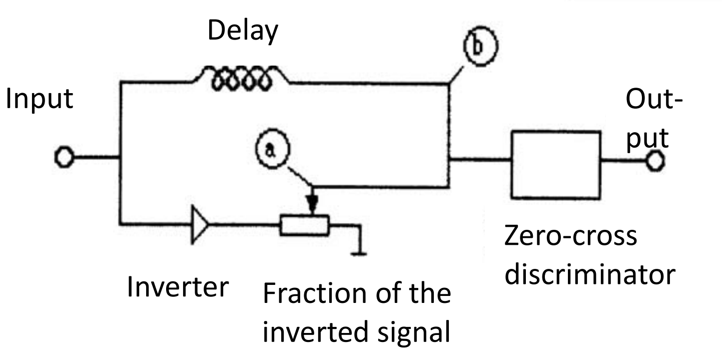
- Amplification of the preamplifier signals
- Signal forming for further electronic processing

In both cases the main amplifier must not change the desired information. The strong proportionality between input and output signal (necessary in experiment 5 for the amplitude measurement) is not important for this experiment. Instead, the time measurement in this coincidence experiment needs a fast response, which is why a Timing-Filter-Amplifier (TFA) is used as a main amplifier.

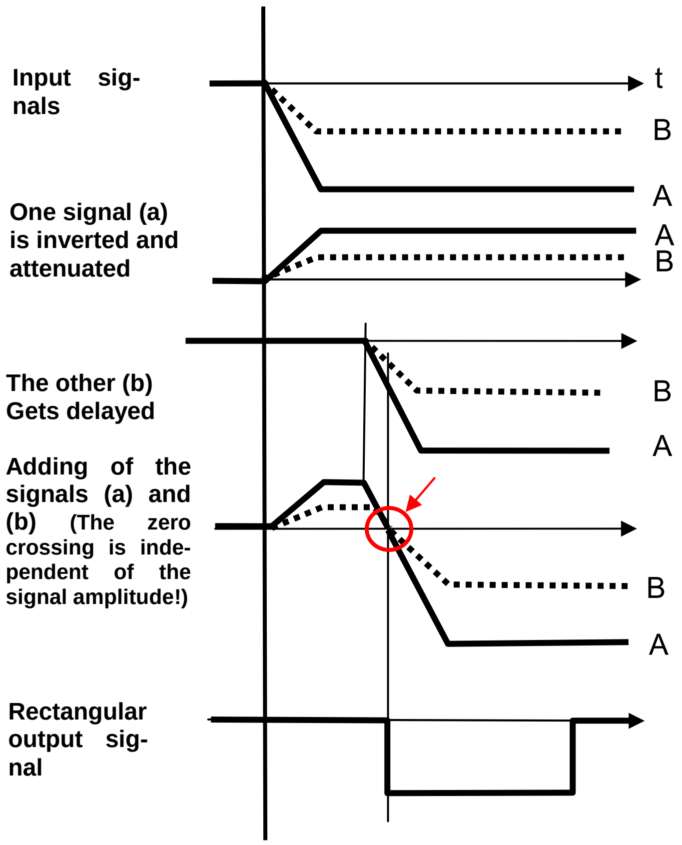
With the TFA, signal shapes can be changed and the signal-to-noise-ratio can be improved for the time measurement. Through suitable choice of the built-in differentiator and integrator elements, the rise time of the voltage pulse at the output can be optimised for the further processing.

## E.4.2. The Constant Fraction Discriminator Amplifier (CFD)

For the exact time measurement that is needed in coincidence experiments, the point in time in which a detector signal arrives must be determined as independently from the signal amplitude as possible. This is usually obtained with a constant-fraction-technique: The signal gets split at the input of the module. One (in the figure shown above) signal is delayed with a cable of corresponding length (external delay) (b). The other signal is inverted and attenuated by a constant fraction (a). Then, both signal parts get added (a+b). The zero crossing of this signal is internally determined with a so-called zero-crossing discriminator and a rectangular output signal (a time signal) is generated.




In the right-hand figure, the individual stages of the signal processing in the CFD are shown again for a signal A with a high amplitude, and a signal B with a low amplitude. The beginning of the time signal is therefore independent of the amplitude and rise time of the input signal. The time signal only contains information about the exact time of the arrival of the detector signal and no more information about the original signal amplitude.





Altogether, four separately working CFD-Amplifiers are located inside the QUAD-CFD-module, but only two of them will be used. The shape of the output signals of the CFD-amplifiers can still be varied. For this purpose, you find three control elements on the front panel only adjustable with a screwdriver (T, Z and W). These settings are already optimised and must not be changed. If you are interested, the setting of these elements is described in the chapter on background knowledge.

☞ **Changing the CFD-settings is only allowed after consulting the supervisor!**

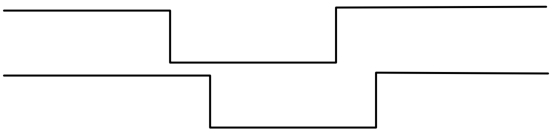
## E.4.3. The coincidence unit

Maybe you have wondered about the reasons for the effort of a constant-fraction-technique to determine a coincidence that can already be observed with the oscilloscope.

Let us summarise what we have learned until now and examine the rectangular time signals again (it should not trouble us that the real signals naturally don't have the ideal rectangular form shown here). In a coincidence, each detector will produce such a signal in its branch.

Detector 1:

Detector 2:



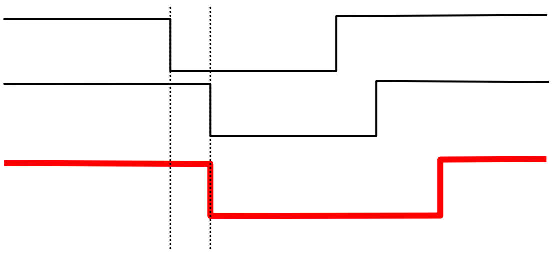
Even though this constitutes a coincidence, the two signals will only seldom be observed as exactly simultaneous in the oscilloscope. This is mainly due to the fact that the signals are unequally delayed when processed through preamplifier, TFA, CFD and connecting cables.

With the help of an electronic "AND"-gate (logical "AND"), the coincidence of the two rectangular signals can easily be determined.

Detector 1:

Detector 2:

(Detector 1) AND (Detector 2)



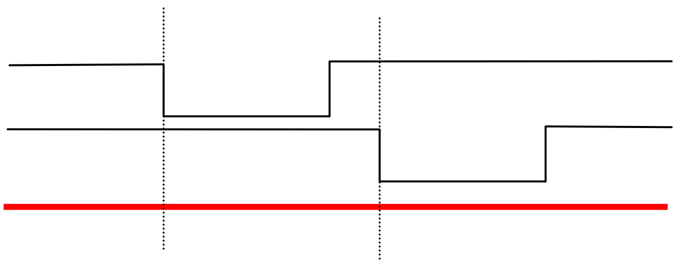
You can see that the signal "(Detector 1) AND (Detector 2)" is formed exactly then, when the falling slope of the 2nd rectangular signal occurs within the 1st rectangular signal. The length of the new signal can be set via the electronics.

If there is no overlap in time, no new signal is formed:

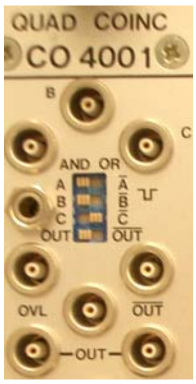
Detector 1:

Detector 2:

(Detector 1) AND (Detector 2)



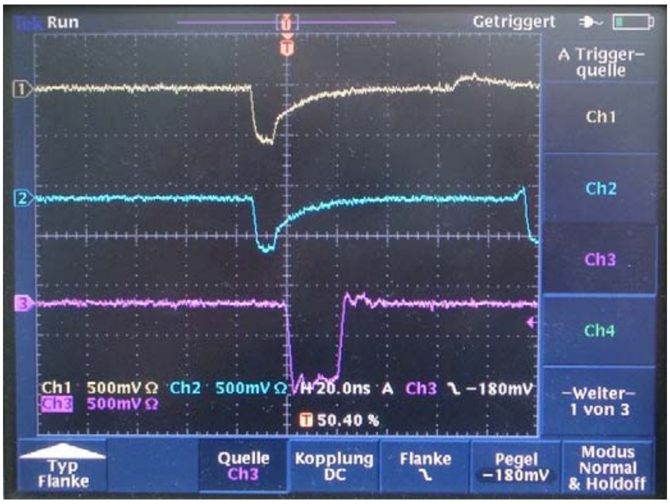
This logic gate is contained in the so-called "Quad-coincidence-Unit". It is self-made by GSI and contains four such gates. It forms a logic signal at the respective output channel, when the signals in the inputs A, B and C have the corresponding values. The logic operation (AND or OR) can be chosen with four miniature switches (see figure). The length of the output signal is fixed to 20ns.




If, as in this case, the signals from the CFD are put into the channels A and B, the correct setting is therefore "A AND B AND (NOT C)", since the no input is plugged into channel C.

The figure below shows the input signals A (Ch1, above), B (Ch2, middle) and the output signal OUT (Ch3, below) of the Quad-coincidence-unit:

☞ Display all logic signals on the oscilloscope as shown here (the settings are saved as "Settings 3"). For this purpose, connect the three LEMO-cables from the coincidence unit with the inputs of the oscilloscope: A→Ch1, B→Ch2, Out→Ch3. Switch on the third channel and trigger consecutively on Ch1, Ch2 and Ch3. Interpret your observations.




## E.4.4 Timer and Scaler

Now the coincidence signals need to be counted. To that end, the output signals of the coincidence unit are put into an electronic counter (scaler), which gets its gate from an adjustable timer.


☞ Familiarise yourself with the operation of the Timer/Scaler.

- Before every new measurement, the scaler has to be reset to zero:
  - Left tumbler switch to "OFF"
  - Press the red RESET-button
  - Left tumbler switch back to "ON"
- Start the measurement by pressing the "Start"-button on the timer
- Depending on the set time period, the measurement gets stopped automatically after a certain time. Choose the setting "2" (32s).
- By pressing the "Stop"-button, a running measurement can be interrupted prematurely.

## *E.5. Measuring the time spectrum*

After adjusting the electronics, the temporal succession of the detectors is not yet optimised. Because of the usually unknown processing times of the electronic components, it can happen that the logic signals do not reach the coincidence unit simultaneously, even though the two gammas reached the detectors at the same time. This is corrected with the help of an additional fixed signal delay in one detector branch and a variable, adjustable delay in the other branch (delay box with 0 to 63 ns delay, see circuit diagram above). With the following technique, you can determine the optimal delay time for this branch.

☞ First set the optimal delay time at the delay box via the oscilloscope with the help of the picture on the previous page.

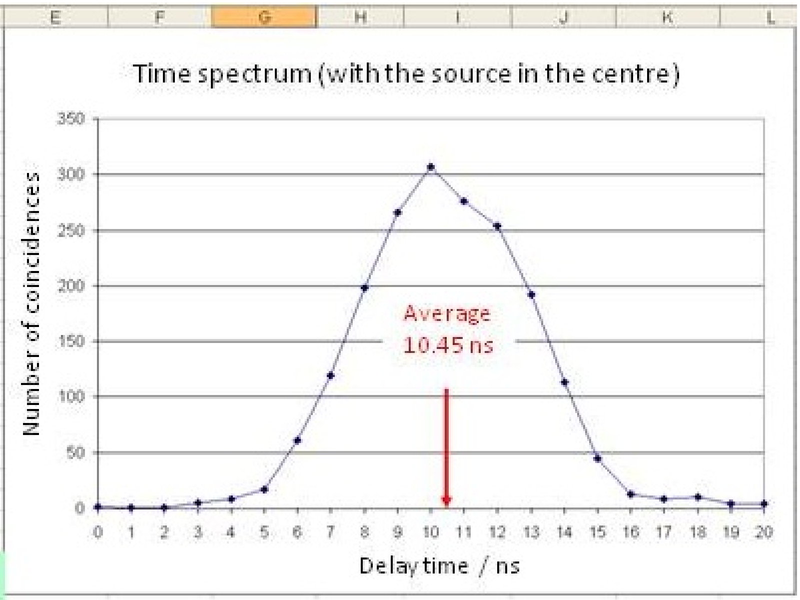
☞ Vary the delay time in 1ns-steps both towards longer and shorter delay times and record the coincidence count rate.

**Take care:** In this measurement, the cables from the coincidence unit (CO4001) must stay connected to the oscilloscope inputs. Because of the danger of signal reflections at loose cable ends, no cables must lie around unconnected.

☞ Record the results in a coordinate system (millimetre paper or EXCEL diagram, see below). Put the delay time on the x-axis and the coincidence count rate on the y-axis. Expected is the following distribution: With too long or too short delay times, no real coincidences can be observed. With one certain delay time the mean temporal overlap of the two logic signals is optimal and the coincidence count rate reaches a maximum.

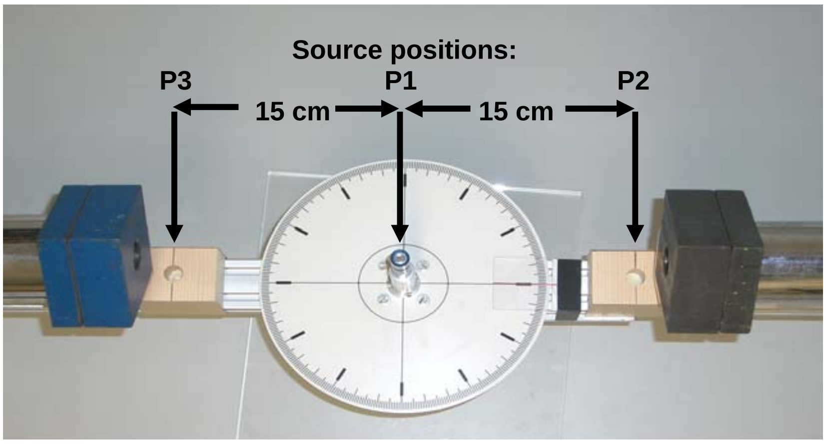
You can determine the optimal delay time by forming the arithmetic mean of the distribution. In the EXCEL-example below, the product A*B is calculated in the column D. All these products get summed up and the sum is divided by the sum of all values in column B. These mean value of the distribution is the optimal delay time. Its value rounded to 1ns shall be used in the remainder of this experiment.

| | A | B | C | D |
|---|---|---|---|---|
| 1 | | | | |
| 2 | Measuring the time spectrum | | | |
| 3 | t / ns | N | | |
| 4 | 0 | 2 | | 0 |
| 5 | 1 | 1 | | 1 |
| 6 | 2 | 1 | | 2 |
| 7 | 3 | 5 | | 15 |
| 8 | 4 | 9 | | 36 |
| 9 | 5 | 17 | | 85 |
| 10 | 6 | 61 | | 366 |
| 11 | 7 | 119 | | 833 |
| 12 | 8 | 198 | | 1584 |
| 13 | 9 | 266 | | 2394 |
| 14 | 10 | 307 | | 3070 |
| 15 | 11 | 276 | | 3036 |
| 16 | 12 | 254 | | 3048 |
| 17 | 13 | 192 | | 2496 |
| 18 | 14 | 113 | | 1582 |
| 19 | 15 | 45 | | 675 |
| 20 | 16 | 13 | | 208 |
| 21 | 17 | 9 | | 153 |
| 22 | 18 | 10 | | 180 |
| 23 | 19 | 4 | | 76 |
| 24 | 20 | 4 | | 80 |
| 25 | | | | |
| 26 | Sum | 1906 | | 19920 |
| 27 | | Average | | 10.45 |



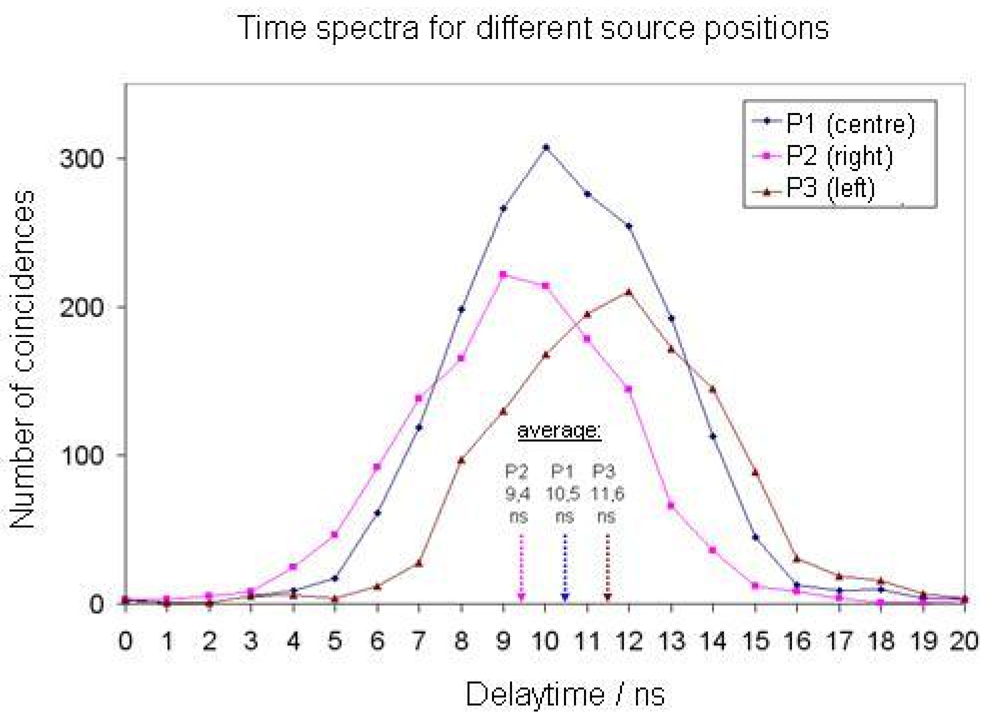
## E.6. Measuring the speed of gammas

In the next part of the experiment, the speed of the coincident gammas shall be measured. To this end, two additional mountings for the source are placed just before the lead collimators (see figure below). If P1 is the position of the source just in the middle of the two detectors, then the source in position P2 is 15cm closer to the left (moveable) NaI-detector. The opposite applies to position P3. For the understanding of the results, it is sufficient to make clear that between the two source positions P2 and P3, the path length difference to the NaI-detectors is 30cm.




☞ Put the source into positions P2 and P3 successively and record a time spectrum as in task E.5.

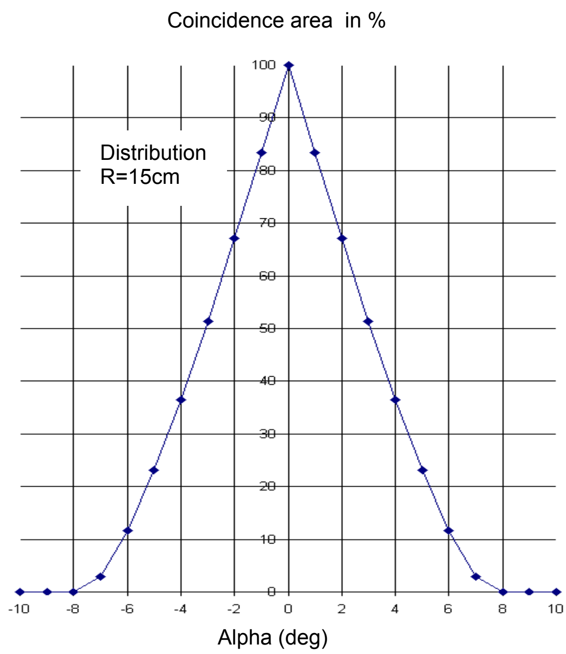
☞ Depict all time spectra in a diagram and calculate the optimal delay time via the mean value. Interpret your measurement and calculate the speed of the gammas with your results.



## *E.7. The measurement of the gamma-gamma angular distribution*

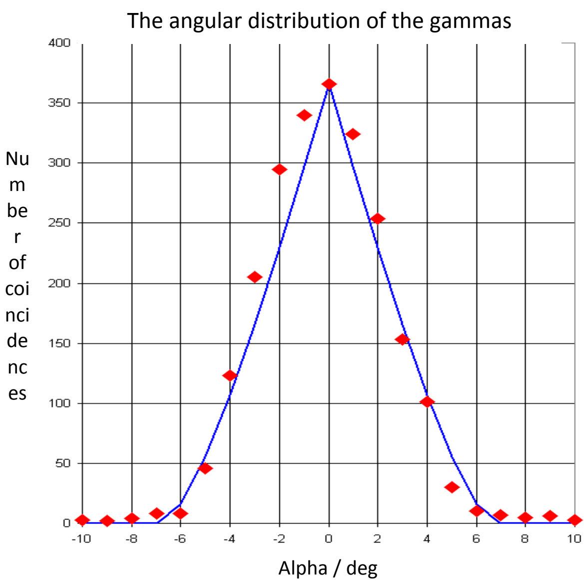
In position P1, the two NaI-detectors are located at the same distance (R=15 cm) from the Na-22-source in an adjustable angle. In the last part of the experiment, it shall be verified that the gammas of the annihilation radiation from the source indeed get emitted in opposite directions. Evidently, you have to change the angle between the two NaI-detector is small steps and record the coincidence count rate against the angle. Before beginning with this measurement, one should think carefully what result can be theoretically expected in such a measurement.

☞ Re-read in chapter B.3. Calculating the coincidence surface how to determine the correlation between the set angle $\alpha=180^0-\varphi$ and the "coincidence surface" as overlap of two circles. This coincidence surface is proportional to the expected coincidence rate.




When $\varphi$ = 180°, i.e. $\alpha$ = 0° one would expect the maximum of the coincidence count rate. Because of the circular shape of the lead collimators, a sharp, nearly triangular shape of the counting rate against the set angle results. Apart from the set angle $\alpha$, the radius r=1cm of the collimators and the distance R (measure!) of the collimators have to be considered in the calculation.

**This calculation is included in the EXCEL-worksheet ("Coincidence spatial angle") found on the computer at the experiment station.**




Alpha (deg)

☞ Record the coincidence rate against the angle $\alpha$ in the range $-10^\circ \le \alpha \le +10^\circ$ in steps of 1° and plot it (red dots in figure on the left).

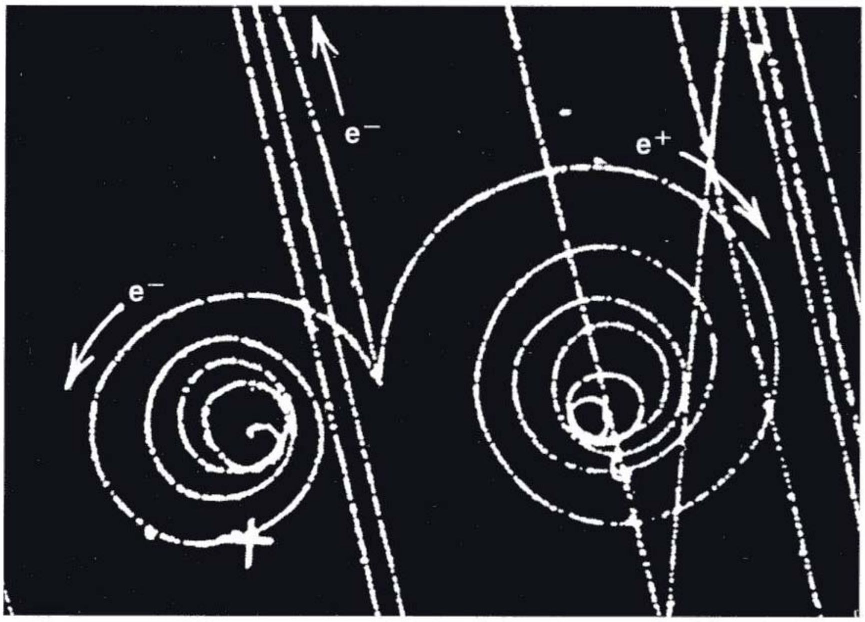
☞ Compare the measured angular distribution with the expected theoretical distribution. Try to plot the measured angular distribution and the conveniently scaled theoretical distribution into one diagram (see left diagram: Theory – blue, measurement – red).

# Background knowledge

## *B.1. The positron and the $e^+$-$e^-$ annihilation radiation*

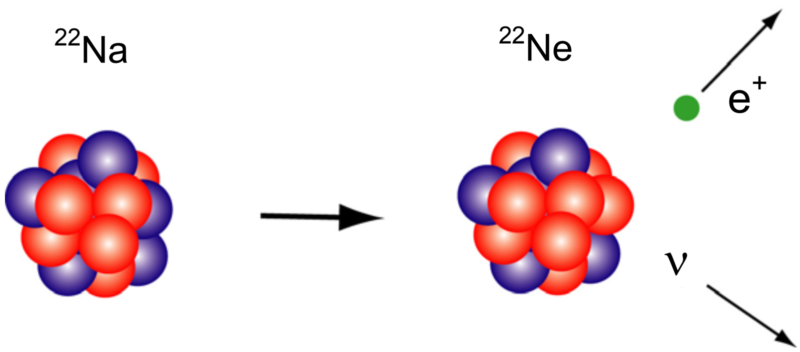
Contrary to natural radiation, positive electrons, so-called positrons, are common in the decay of artificial radioactive isotopes. They differ from electrons only through the positive sign of their charge. Positrons are emitted by nuclei with a proton excess. The process involves the conversion of a proton to a neutron.

The positron (**$e^+$**) was discovered in 1932 by ANDERSON in the sampling of cloud chamber pictures which were generated by cosmic radiation. The chamber was placed in a magnetic field so that the tracks of electrons and positrons curved in opposite directions due to their opposite charge sign. In 1934, the JOLIOT-CURIE couple also observed positrons in the decay of artificially created radioactive elements.




Let us examine the process using the example of the isotope $^{22}$Na that is also used in the experiment. Contrary to the “normal” Isotope $^{23}$Na, which we know from table salt (NaCl), $^{22}$Na has one neutron less and is therefore unstable. It decays into the stable $^{22}$Ne-isotope with a half-life of 2.60 years by converting one proton into a neutron in the nucleus.

$$^{22}_{11}\mathrm{Na} \rightarrow ^{22}_{10}\mathrm{Ne} + e^{+} + \nu + E_{kin}$$




As one can see, the conversion of a proton into a neutron also generates another particle, the neutrino ν. Through emission of the positron, the nuclear charge is lowered by one. The decay of a free proton is energetically impossible, as the mass of the proton is smaller than the mass of the neutron. One has to ask why an excess of protons in the nucleus is not just eliminated by emission of a proton. The justification is the following: to emit a proton, energy of the order of the mean binding energy per nucleon (~8MeV) has to be available. In contrast, the generation of a positron just requires the energy equivalent to its stationary mass of 0.511 MeV plus the energy that corresponds to the mass difference between the proton and the neutron. Since the conversion of a proton to a neutron increases the binding energy as the electrostatic charge decreases, the emission of a positron only requires an energy of about 1 MeV, substantially less than the emission of a proton.

The positron is the electrons antiparticle and has the exact properties apart from its electric charge. It is part of the so-called antimatter and therefore does not usually exist in our world of matter. However, if it is, as in our example, emitted from a nucleus in a decay process, it will then be slowed down by many consecutive collisions and finally form a short-lived positronium-system with an electron, in which the positron and the electron revolve around a common centre of mass. This system has a very short lifetime of several nanoseconds. In its decay, the electron and positron annihilate one another.

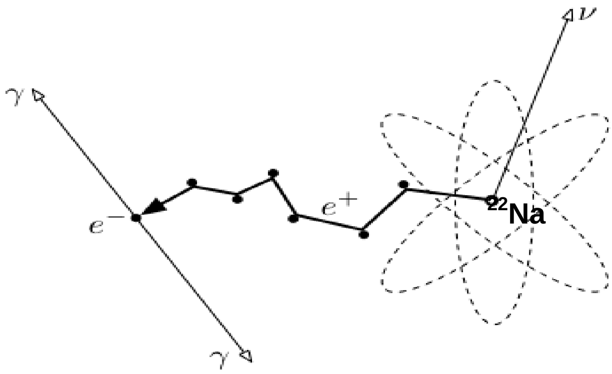
The positron-electron pair vanishes and its entire mass

$$m = m_{electron} + m_{positron} ,$$

is converted into radiation energy E after Einstein's famous equation

$$E = m \cdot c^2$$

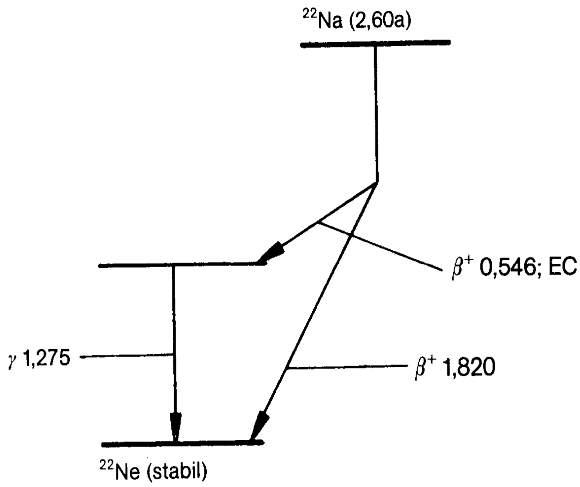
(speed of light c=300000 km/s )




This disintegration, in which matter effectively “vanishes” from our world, is also called (pair) annihilation. Due to conservation of momentum, two gammas are generated with an energy of 511 keV each (stationary mass of electron/positron) and are emitted in exactly opposite directions.

## B.1.1. The Na-22 source

The sodium-22 source is shrink-wrapped and fixed in polyester-foil. This slice is additionally covered with a stainless steel foil (thickness 0.02 mm; ~16 mg/cm$^3$). Apart from the positrons, γ-radiation and annihilation radiation (**) are emitted. The decay scheme with the corresponding energies is shown in the adjacent figure.

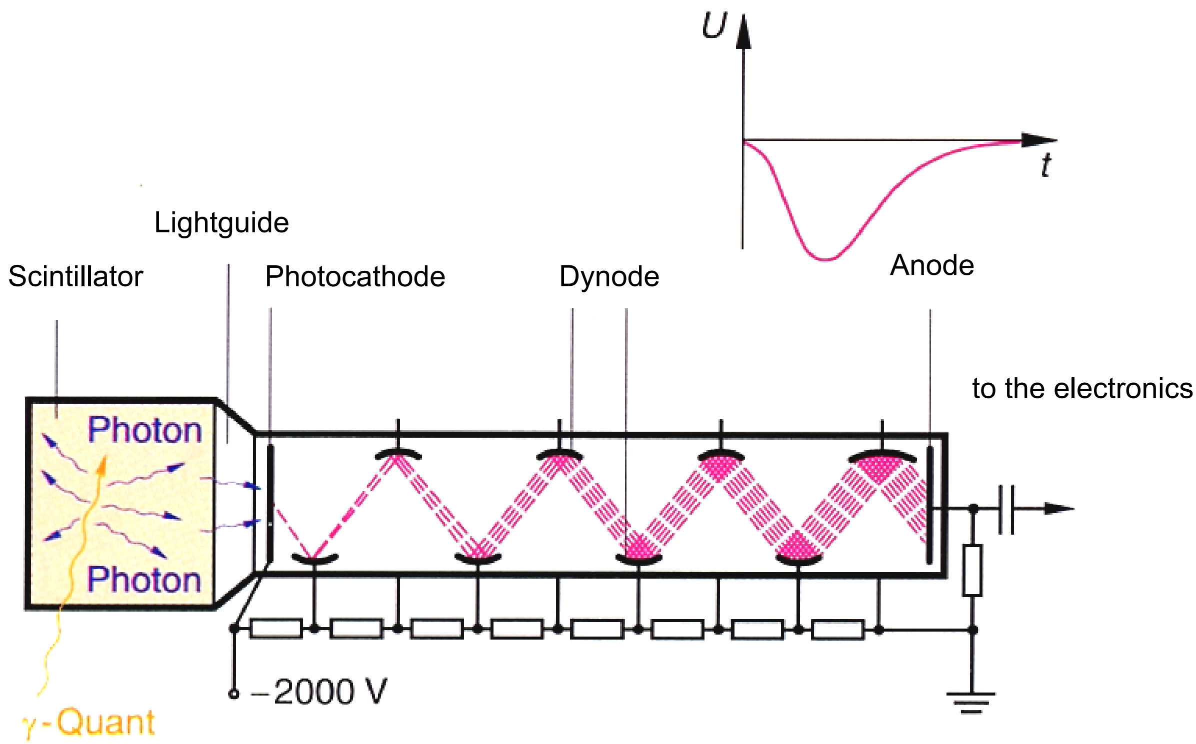



| | Half-life | β-Energy (MeV) | Transition probability | γ-Energy (MeV) | % Emitted |
|---|---|---|---|---|---|
| Na-22 | 2,60a | 0.546 | 90.49 | 0.511** | (from β+) |
| | | 1.820 | 0.05 | 1.275 | 99.95 |
| | | EC | 9.46 | | |

## *B.2. Detection of gamma-radiation with a NaI-scintillation detector*

The first scintillation detectors consisted of a zinc sulphide screen and a microscope. If, for example, α- or γ-radiation hits the zinc sulphide screen, they generate short light impulses which can be observed with a microscope. With this method, RUTHERFORD investigated the scattering of α-particles from atomic nuclei. Since the human eye cannot reliably detect these light pulses, the measurement technique was soon discontinued and was only employed once it became possible to electronically process the light pulses with a photo multiplier (secondary electron multiplier).

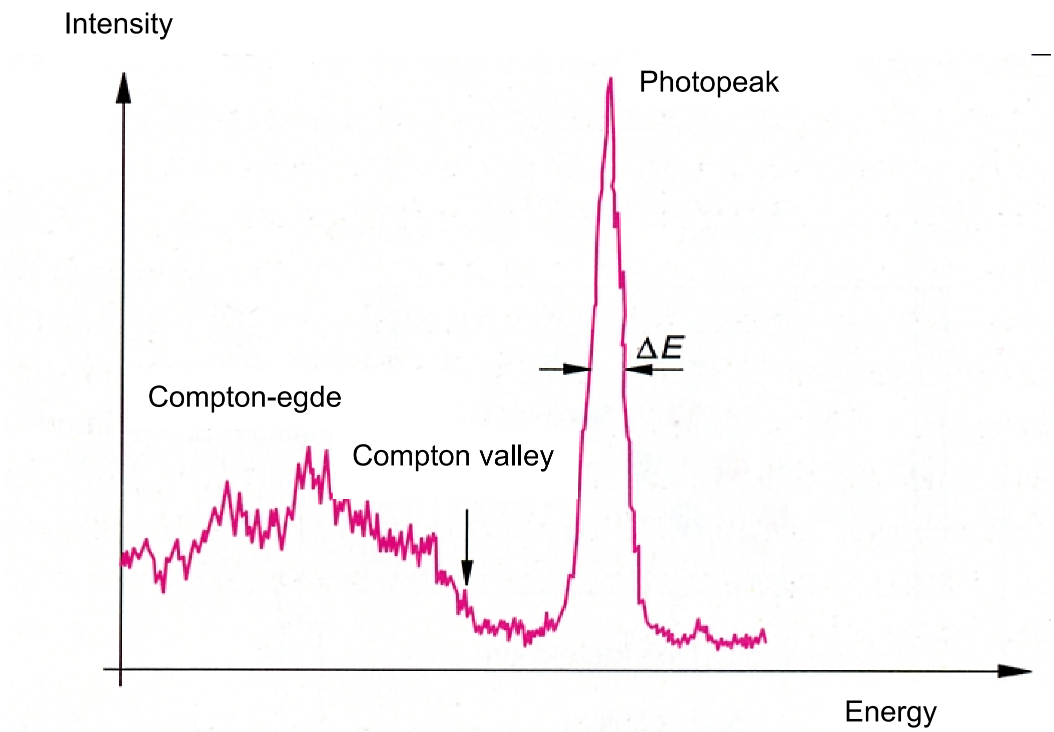
The basic configuration of a modern scintillation detector is shown in the next figure. Solid, fluid inorganic or organic materials are suitable. Sodium iodide crystals, doped with Thallium (NaI(TI)) are often used. The Thallium atoms serve as scintillation centres. The advantage of scintillation detectors is the achievable size: crystal scintillators can reach sizes in the order of magnitude of several litres; the volumes of plastic or liquid detectors are unlimited. Therefore, they have high detection efficiency for gamma radiation.




A gamma photon can transfer part of its energy or even its entire energy to electrons in the scintillator material. The electron then loses its energy by lifting other electrons into higher energy states along its track within the scintillator. These excited states then decay again by emission of photons. Through a light conductor, a part of the photons reaches the photo cathode of the photo multiplier and causes electrons to be emitted from it. These electrons are accelerated in a chain of electrodes, so-called dynodes, in such a way that every electron causes two to five further electrons to be emitted from every dynode. The electrons then get collected on an anode and generate a voltage pulse on a resistor. Amplification ratios of $10^9$ can be reached that way, meaning that every electron generates about a billion secondary electrons in the photo multiplier.

A small number of photons generated in the scintillator therefore cause a measurable electric impulse at the output of the photo multiplier. The amplitude of the pulse is proportional to the energy that the incident gamma transferred to electrons in the scintillator. The voltage pulses get further processed electronically. The exact processing depends on the problem: if the exact energy of the incident gamma is required, then the energy proportional output of the multiplier is used and the pulse is amplified linearly. The impulse is converted into a digital number depending on its height. These numbers are registered and plotted in a histogram. Like this it is possible to obtain an energy spectrum of the gamma radiation of a radioactive source.

The figure shows the spectrum obtained from the mono-energetic 511 keV radiation of a Na-22 source. The energy plotted on the x-axis is proportional to the amplitude of the registered primary pulses, the amount of registered pulses of a certain height corresponds to the intensity. A relatively sharp maximum can be observed, the so-called photo peak, which results from the gamma transferring its entire energy to an electron in a single process,



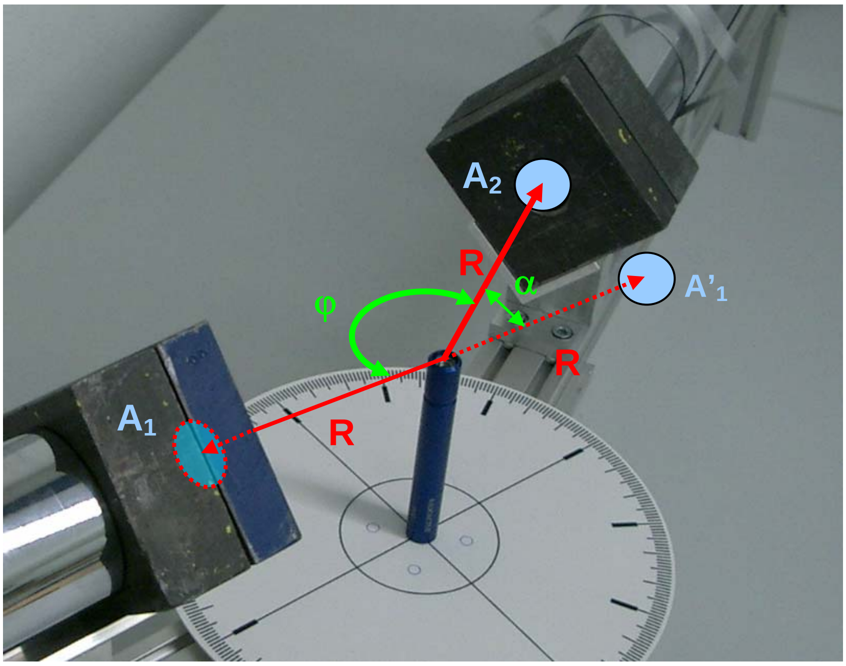

the photo-electric effect. The electron then causes the excitations in the crystal, whose decay causes the photon registered as light pulses. Apart from the photo peak, radiation of a lower energy is registered. This is due to the Compton scattering occurring in the crystal. The gamma photon transfers just a part of its energy to an electron. The amount of energy transferred depends on the scattering angle and has a maximal value for backwards scattering. The energy of the electrons involved in this process is registered, as above, as a light pulse of a certain energy. The Compton edge in the spectrum originates from electrons which got their energy through backwards scattering. Further radiation with energies below the Compton edge is also registered. This is caused by scattering processes with angles smaller than 180°.

The photo peak of the scintillator spectrum has the width $\Delta E$ at half of its height. The width results from stochastic fluctuations in the process of registering the radiation: The gamma generates a photo electron, which on its way through the scintillator causes light photons to be emitted. The number of light photons and the energy of the gamma are proportional. But only a part of the photons reaches the photo cathode; another part is absorbed in the scintillator crystal and the light conductor. The light photons hitting the photo cathode of the multiplier cause electrons to be emitted from it with a probability of 0.05 to 0.1. It is noticeable that the number of electrons generated in the multiplier is several orders of magnitude smaller than the number of photons created in the scintillator. The fluctuation of the number of electrons, which are primarily generated in the multiplier determines the width $\Delta E$ of the photo peak and therefore also the energy resolution $\Delta E/E$. Since there are gamma spectra whose energy values lie close together, a scintillator won't be able to separate them anymore.

**Summary:** In scintillation detectors, gammas transfer their energy to electrons, which cause light photons to be emitted in the material. Scintillators have a high detection efficiency for gamma radiation. Their disadvantage is their relatively small energy resolution $\Delta E/E$ of ~10%.

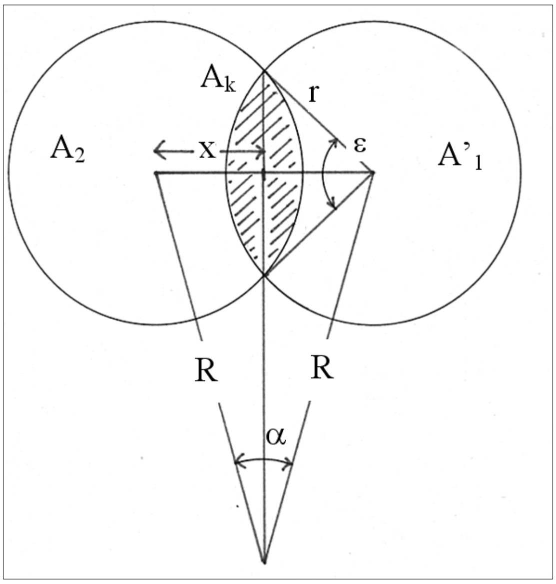
## *B.3. Calculating the coincidence surface*

Let us look at the geometry of the Na-22-source and the two detectors in the picture below. Let us assume, a gamma of annihilation radiation hits the surface $A_1$ on the left detector. The entry surface $A_2$ of the second detector is at the same distance R under the set angle $\varphi$ < 180°. Then the simultaneous second gamma is emitted in the opposite direction along the dashed red arrow into the surface $A_1$', will miss the right detector by the angle $\alpha = 180^0 - \varphi$ and will not be detected. Consequently, no coincidence can be observed. Coincidences will only be observed if the angle $\alpha$ is set to such a small value that the surface $A_2$ overlaps with the projected surface $A_1$'.




This is shown in the sketch on the left: It shows the two circular surfaces $A_2$ and $A_1$'; the radius r is shown in the right circle, but is the same for the left. The hatched overlap surface Ak is the so-called coincidence surface, which depends on the set angle.
In this picture, the two circle centres are separated by the distance 2x, which is directly dependent on the angle $\alpha$.

(1) $x = R \cdot \sin\left(\frac{\alpha}{2}\right).$




The distance x is linked to the circle radius r:

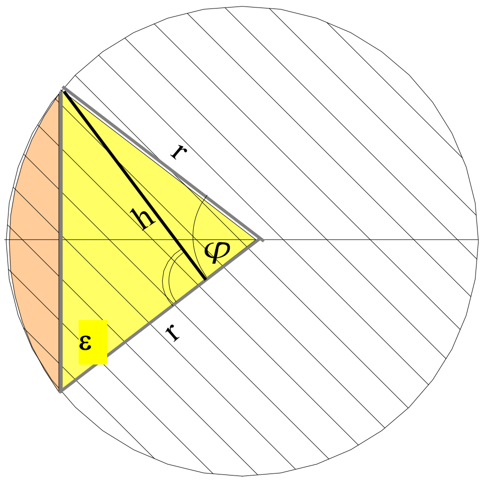
(2) $\frac{\varepsilon}{2} = \arccos\left(\frac{x}{r}\right)$, or

(3) $\varepsilon = 2 \cdot \arccos\left(\frac{x}{r}\right).$

We shall now look only at the right circle (figure). The surface of the sector $A_{Sector}$ limited by the angle ε is easy to calculate. If ε is given in radians, then:

$$A_{Sector} = \frac{\varepsilon}{2 \cdot \pi} \cdot \pi \cdot r^2 = \frac{\varepsilon}{2} \cdot r^2$$

The sector can then be divided into the yellow triangle and the orange circle segment




The perpendicular to r is:

$h = r \cdot \sin \varepsilon$,

which results in the yellow triangular surface:

$$A_{triangle} = \frac{1}{2} \cdot r \cdot h = \frac{r^2}{2} \sin \varepsilon.$$

The orange segment is then the difference

$A_{Sector} - A_{triangle}$.

The coincidence surface is now the exact double of this circle segment:

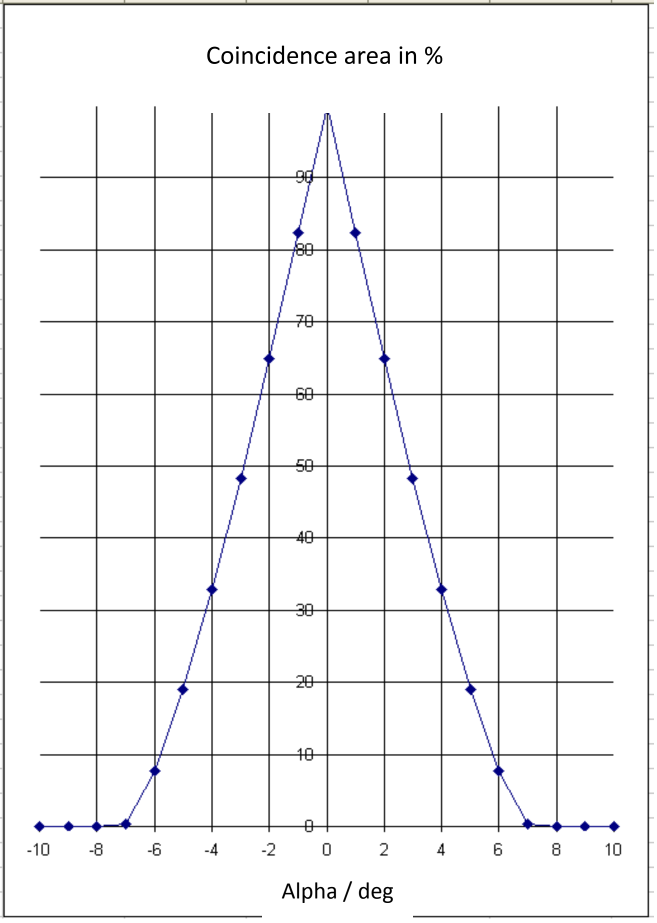
(4) $A_K = 2 \cdot \left(A_{Sector} - A_{triangle}\right) = \frac{2 \cdot r^2}{2} \cdot (\varepsilon - \sin\varepsilon) = r^2 \cdot (\varepsilon - \sin\varepsilon).$

The calculation of the coincidence surface $A_K$ as a function of the set angle $\alpha$ from the equations (1), (3) and (4) is done here simply with the help of an excel spread sheet:

Table for gamma-gamma coincidence

| | Input field |
|---|---|
| R/cm= | 16 |
| r/cm= | 1 |

| Alpha/deg | x/cm | Epsilon | Ak / cm^2 | Ak / % |
|---|---|---|---|---|
| | 2.088419076 | 0 | 0 | 0 |
| -14 | 1.949909494 | 0 | 0 | 0 |
| -13 | 1.81125142 | 0 | 0 | 0 |
| -12 | 1.672455412 | 0 | 0 | 0 |
| -11 | 1.53353204 | 0 | 0 | 0 |
| -10 | 1.394491884 | 0 | 0 | 0 |
| -9 | 1.255345532 | 0 | 0 | 0 |
| -8 | 1.11610358 | 0 | 0 | 0 |
| -7 | 0.976776633 | 0.431869 | 0.0133 | 0.423353327 |
| -6 | 0.8373753 | 1.156665 | 0.2411988 | 7.677596921 |
| -5 | 0.697910198 | 1.596642 | 0.5969759 | 19.0023329 |
| -4 | 0.558391947 | 1.9567 | 1.0302419 | 32.79361704 |
| -3 | 0.418831173 | 2.277277 | 1.516626 | 48.27570443 |
| -2 | 0.279238503 | 2.575591 | 2.0393289 | 64.91385569 |
| -1 | 0.139624568 | 2.861428 | 2.5849144 | 82.28038025 |
| 0 | 0 | 3.141593 | 3.1415927 | 100 |
| 1 | 0.139624568 | 2.861428 | 2.5849144 | 82.28038025 |
| 2 | 0.279238503 | 2.575591 | 2.0393289 | 64.91385569 |
| 3 | 0.418831173 | 2.277277 | 1.516626 | 48.27570443 |
| 4 | 0.558391947 | 1.9567 | 1.0302419 | 32.79361704 |
| 5 | 0.697910198 | 1.596642 | 0.5969759 | 19.0023329 |
| 6 | 0.8373753 | 1.156665 | 0.2411988 | 7.677596921 |
| 7 | 0.976776633 | 0.431869 | 0.0133 | 0.423353327 |
| 8 | 1.11610358 | 0 | 0 | 0 |
| 9 | 1.255345532 | 0 | 0 | 0 |
| 10 | 1.394491884 | 0 | 0 | 0 |
| 11 | 1.53353204 | 0 | 0 | 0 |
| 12 | 1.672455412 | 0 | 0 | 0 |
| 13 | 1.81125142 | 0 | 0 | 0 |
| 14 | 1.949909494 | 0 | 0 | 0 |
| 15 | 2.088419076 | 0 | 0 | 0 |

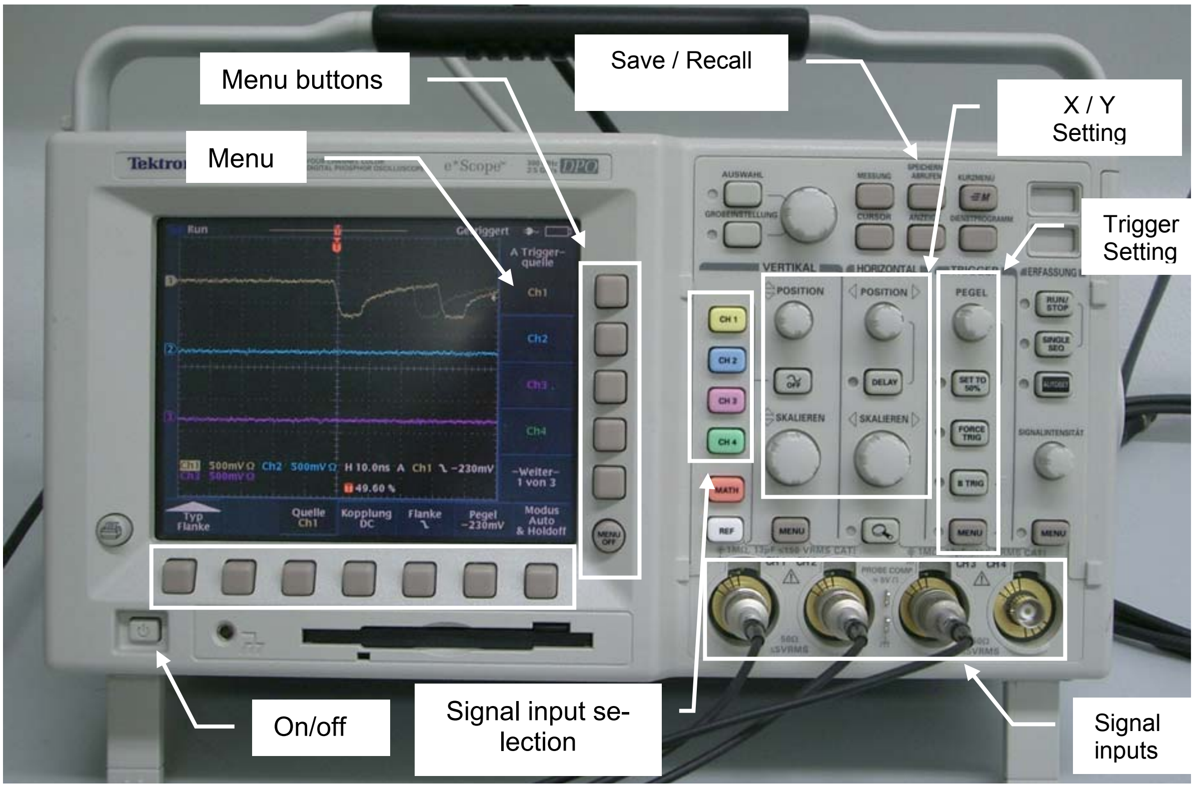



## B.4. Working with the oscilloscope

<u>Functioning</u>

An oscilloscope can be used to graphically display temporal processes. In our case, these are voltages and with a small trick also currents. The easiest way to visualise this is by means of an old scope with a cathode ray tube. This is nothing else than a small TV with a single dot on the screen which can be moved. This dot is constantly moved from the left to the right and its height changed according to the input signal. We put a saw-tooth wave in x-direction as shown in the figure. Running the scope like this would result in a different picture each time the beam moves from left to right and therefore we would not be able to read any useful information. We have to somehow “synchronise” the saw tooth to the input signal. This work is done for us by the trigger. In the normal case, we don’t move the beam. Only once the trigger says: “Now!“ we start a single saw tooth. If the signal is periodic, the trigger happens always at the same point of the function and we get a “stationary” picture on the oscilloscope. The Tektronix-oscilloscope we use in this lab is a digital oscilloscope. That means that it converts the input voltage into a digital value and stores it in its memory. Instead of a move in x-direction, we now have to picture a storage address. On the screen, the storage content is displayed.

This figure shows the digital oscilloscope at your disposal with all its essential control elements.



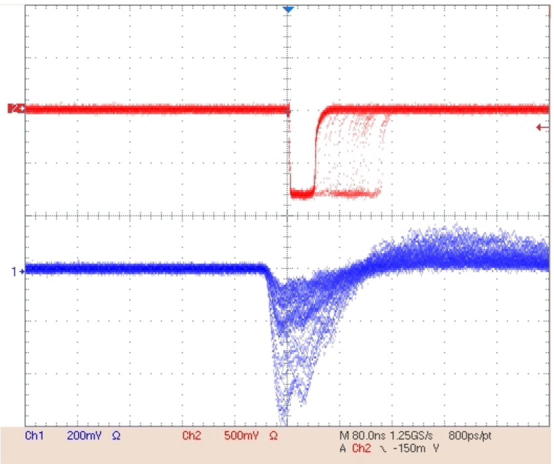

The most important settings:

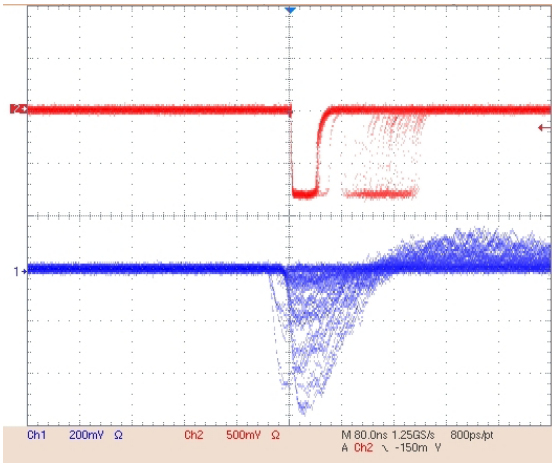
- With the signal input selection buttons, the four oscilloscope input channels Ch1 to Ch4 can be activated.
- The trigger source can be selected with the menu buttons after pressing the trigger menu button. The trigger threshold can be varied with the turning knob “Threshold”.
- The button “Save/recall” accesses a menu, in which to save or recall pre-settings of the oscilloscope
- The knobs “vertical scale” and “horizontal scale” change the signal height and time scale. The former is set for every channel independently, the latter commonly for all channels
- Altogether, four different signals from the four inputs can be displayed at the same time. There is an option of picking one of the four channels to trigger the signal. Alternatively, the trigger menu can also be set so that all signal sources can trigger.

## *B.5. Setting the Constant-Fraction-Discriminator (optional)*

The following settings of the CFD are optional. Their testing has to be first agreed on with the supervisor.

### B.5.1 Threshold Adjustment (“T”)

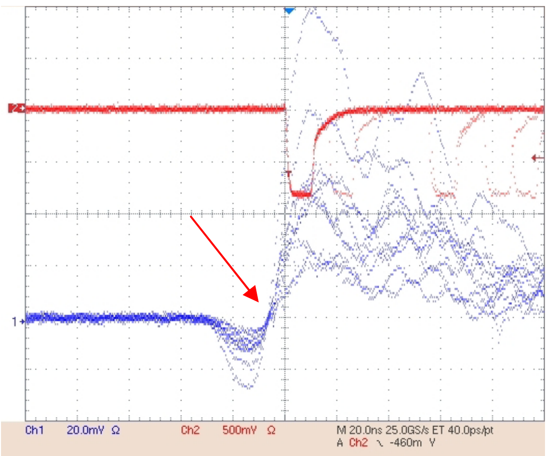


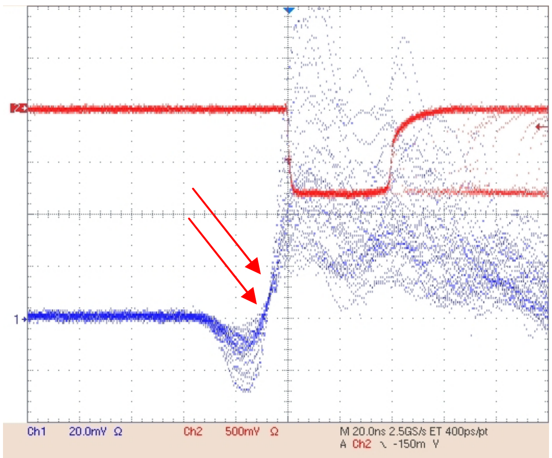




This setting serves to eliminate unwanted low-energy pulses and electronic noise from further processing by putting a threshold. The two oscilloscope pictures show above (red) the rectangular output signal of the CFD that is used to trigger the scope. Below (blue), the input signal of the CFD is shown, so that it can be seen which input signal resulted in a time signal. At the left you see a well-set threshold: all signals are clearly above the noise around the zero. At the right, you see a badly set (too low) threshold, where even the electronic noise has resulted in a time signal.

### B.5.2 Walk Adjustment (“Z“)

On the monitor output “M” of the CFD, the sum signal “a+b” can be read out, which, as explained above, is used by the zero crossing discriminator to form the time signal. The control element “Z” is used to adjust the summing of the signals a and b so that all sum signals have their zero crossing at the same time, independent of their input amplitude. In the left oscilloscope picture (below, blue line), this is well achieved; not so in the right picture.



## B.5.3 Output Width Adjustment  (“W”)

With the last control element “W” accessible on the front panel of the CFD, the length of the time signal can be set. In the above left picture, it is about 10ns, in the right picture about 40 ns (red line above). In this experiment the length of the output signal should be put to 10 ns.

Writing date 16.06.2013

Translated by Eleonora Teresia Gregor and Dr. Kamna Pande from the German script
Last saved by Dr. Kamna Pande