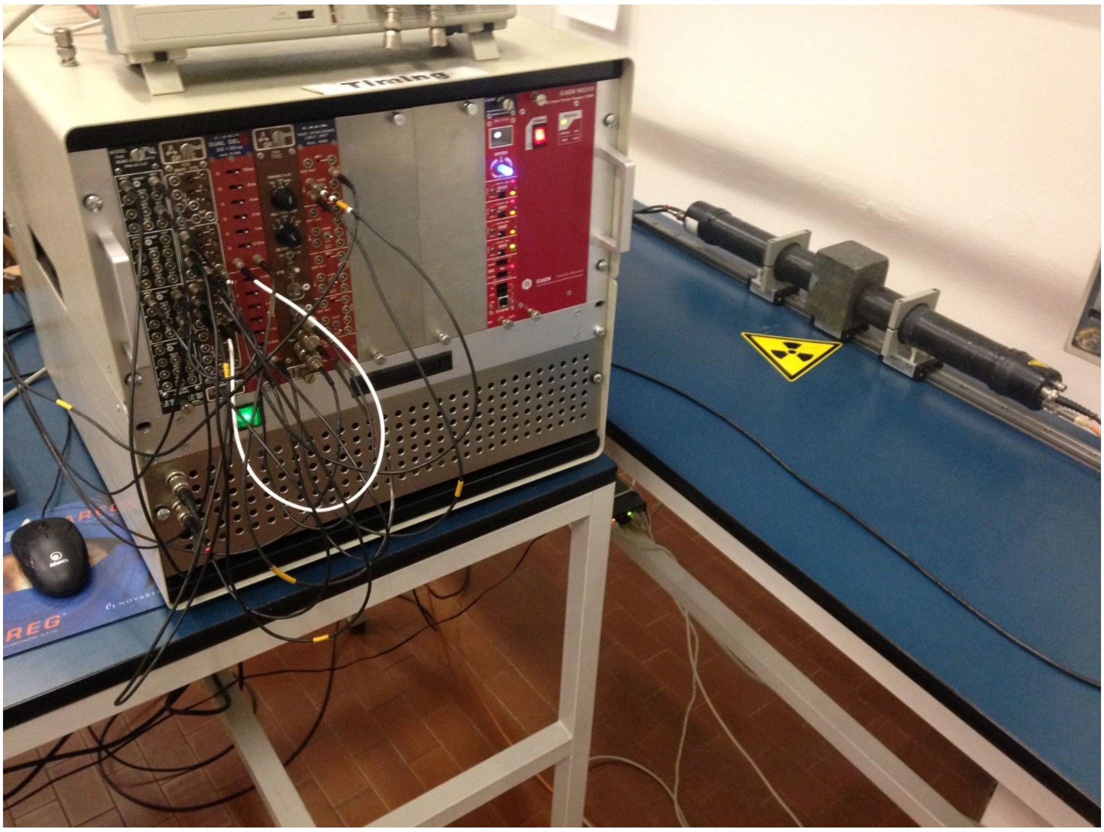
Chapter 10

Experiment # 8

Timing



10.1 Introduction

In order to obtain the best possible timing information it is possible to use a variety of analogue electronics signal processing methods. A commonly used device is the constant fraction timing discriminator module (CFTD). The timing information is used to build "overlap" coincidences between two or more events and to measure time differences by means of the time-to- amplitude converter. However, in many of experiences in the lab, automatic CFTD modules are used, where only the value of the discrimination threshold can be set and the manufacturer takes care of the other parameters of the CFTD. The goal of this experience is to study the accuracy of a time measurement versus a set of parameters of the detector and CFTD. We recall in the following section the operation of the CFTD.
The operating principle of a CFTD is shown in Figure 10.1. The input signal to the discriminator is doubled. The first signal is only delayed for a quantity that corresponds to a fixed fraction of the rising time (about 80%), while the second signal is inverted and attenuated. The two signals are then summed, obtaining this way a bipolar signal. It can be demonstrated that the minimum time dispersion is obtained in the crossing of the zero level. With this technique you can minimize the time uncertainty associated with different amplitudes (or rising times) of the signal.

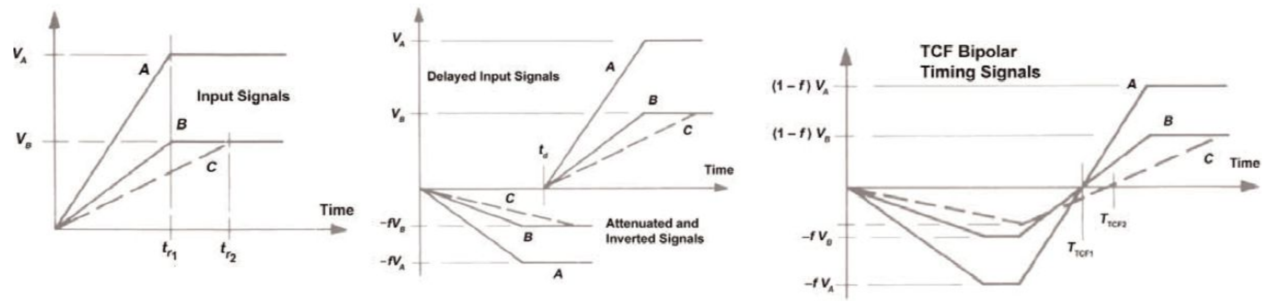


Fig. 10.1: Signal construction in a Constant fraction timing discriminator with compensation for pulse height and rising time.

The electronic diagram for a constant fraction timing discriminator is show in Fig. 10.2.

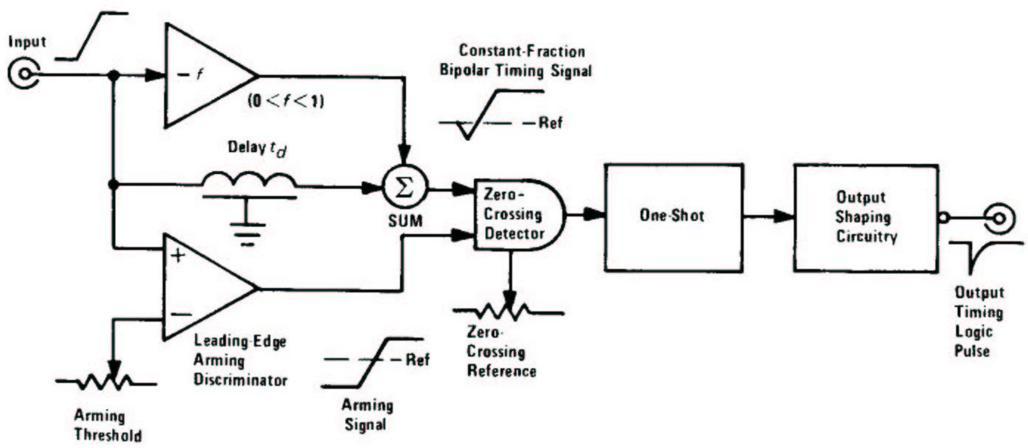


Fig. 10.2: Electronic diagram of a constant fraction timing discriminator.

10.2 Experimental Setup

The experimental setup for the timing experiment is show in Fig. 10.3.

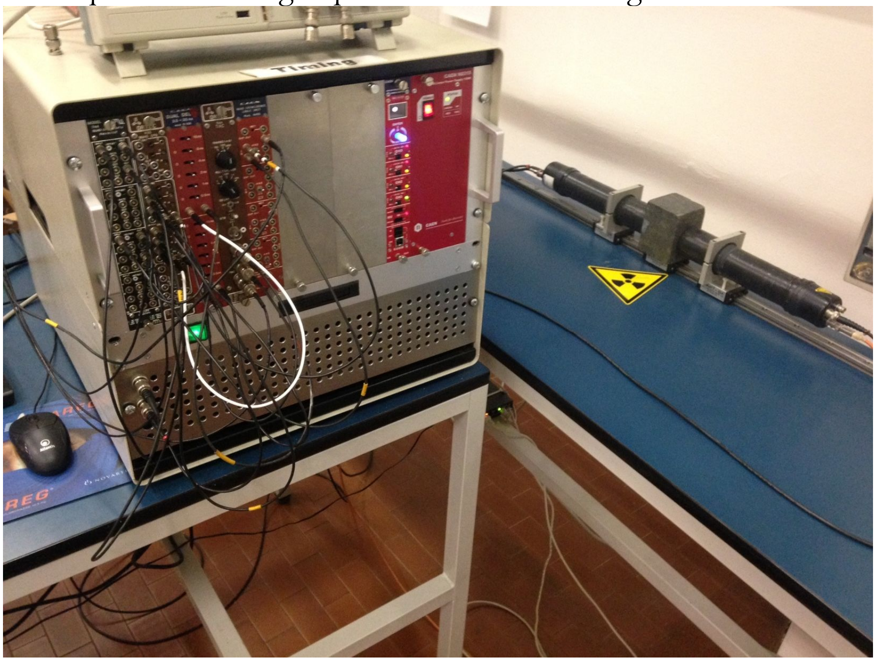


Fig.10.3: Experimental setup for timing experiment.

A ^{22}Na source is collimated using a properly shaped lead brick to obtain a photon beam with a defined collinear geometry. The beam hits two cylindrical organic scintillators EJ-228, with a 5 cm diameter and 5 cm thickness. The light output of these scintillators is collected by a Photonics Photomultiplier XP2020 with voltage divider mod. VD124K/T. This voltage divider contains 14 or 12 dynode and has two outputs: the anode signal (negative) and the signal from the last dynode (positive). During the laboratory you will use only the anode signal.
A CAEN Mod N1471 supplies HV to each detector. Normally you will already find the detectors in operation with set appropriate HV values.
For each detector, the output of the anode is connected to a Quad Linear Gate FAN-IN / OUT mod. Philips 744 for signal splitting without modifying the signal shape.
From FAN-OUT the first signal is connected to the Quad CFD ORTEC mod. 935 shown in Fig. 10.4, and the second one is inserted directly into the acquisition system: a CAEN digitizer mod. DT5751. The digitizer has a sampling rate of 1 Gs/s and a resolution of 10 bit. See Chapter 12.4 for details on the Digital Electronics and Appendix V for the DAQ system.
Each section of the module Quad CFD ORTEC has the following characteristic:

a) Signal acceptance range from 0 to -10 V.
b) Threshold adjustable between -10 mV and -1000 mV. The value can be measured with a multimeter.
c) Three outputs with standard NIM (-800 mV) signal. It is possible to set the width of the signal through a potentiometer from 4 to 200 ns.
d) The internal Delay of CFTD can be set with an external cable.
e) The potentiometer for Walk Adjustment can be used to optimize the zero crossing ($\pm$ 15 mV) point.

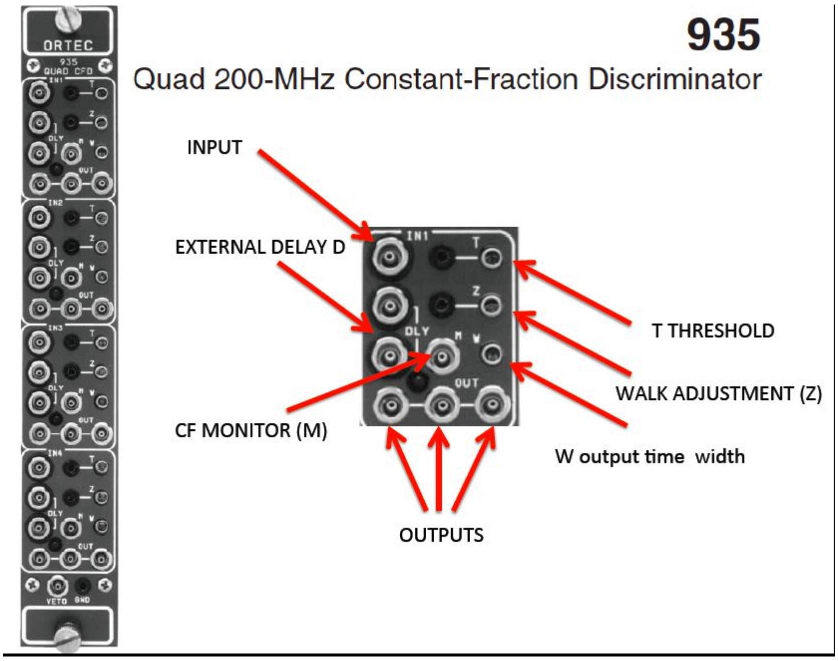


Fig.10.4: The Quad CFD ORTEC mod. 935.

The principle of operation of this specific CFTD can be summarized as shown in Fig.10.5.
The module uses a fixed fraction fV = 20% set by the manufacturer. The input signal is doubled and one of the two signals is attenuated by this fraction. The second signal is inverted and delayed by the external cable. To improve the time resolution of CFTD you can add a delay equal to the 80% of the rise time (if fV = 20%). In this way, when the two signals are summed up, the maximum of the negative polarity of the attenuated signal corresponds to the time where the inverted signal reaches 20%. Since the inverted signal has been attenuated by the same fraction, at that point there will be the zero crossing that will define the time of the event.

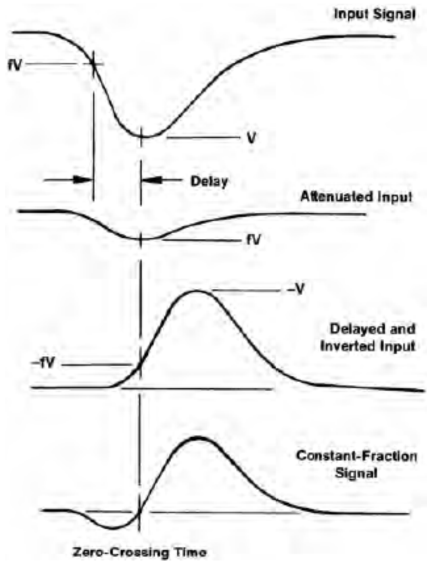


Fig. 10.5: The principle of operation of CFTD mod. 935.

To use this CFTD, using the oscilloscope, you first have to determine the characteristic rise time of the signal, then have to choose a proper length of a LEMO cable that delays the signal for a time corresponding to 80% of the rise time.
The diagram of the electronics for the experiment is show in Fig.10.6.
The CFTD output of detector D#1 is connected to the START of a Time to Amplitude Converter (TAC) and D#2 is connected to the STOP, after a Delay Unit. For the description of TAC see Chap.

12. Finally, the Quad Logic Unit (CAEN mod N455) provides TRG IN for the digitizer. The module allows to get the logic OR or AND between 2 detectors by providing logic output signals with NIM standard (-800 mV).
D#1 and D#2 are connected to channel 0 and 1 of the digitizer whereas TAC output is connected to channel 2.

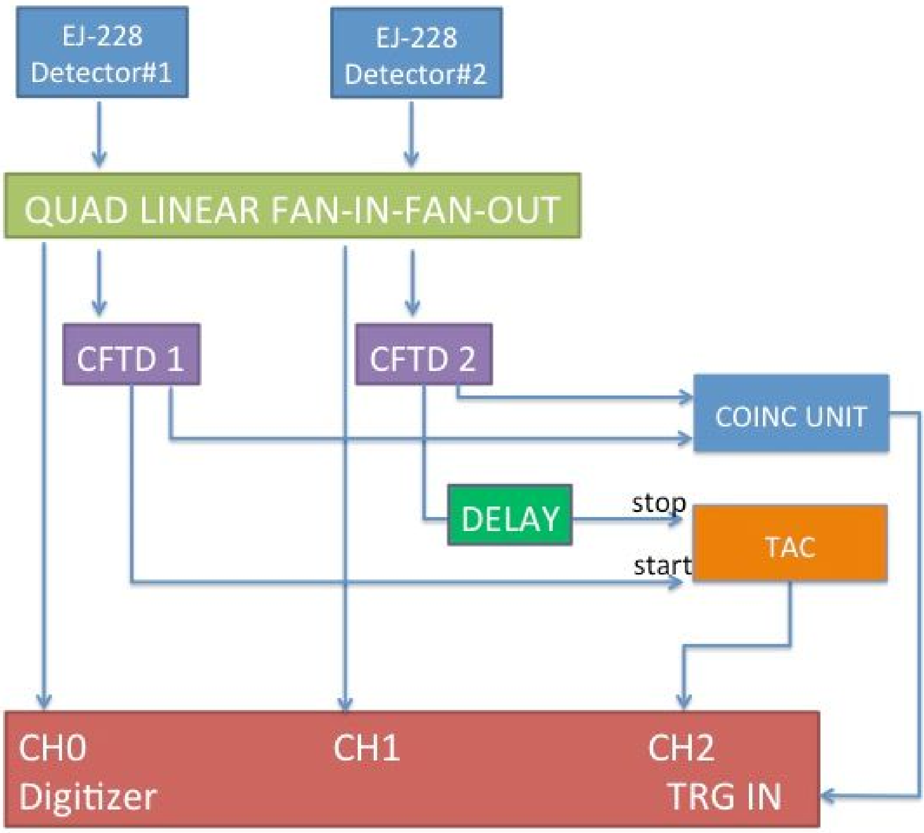


Fig. 10.6: Diagram of the electronics for the timing experiment.

The organic scintillators contain only light elements like Carbon or Hydrogen and the photo-electric cross section of these elements is negligible for the energy used in laboratory (source of ^{22}Na, 511 and 1275 keV). Furthermore, the probability of total absorption of the total energy of gamma-ray through multiple Compton Scattering are negligible, due the small size of the detector. Therefore the response function of the detectors will be dominated by the individual Compton interaction, the result in the energy spectrum is a continuous distribution that corresponds to different angles of interaction, with a "Compton Edge" at the maximum energy kinematically allowed, as shown in Figure 10.7.
The nominal energy of Compton Edge, E_{CE}, i.e. the maximum energy deposit in a photon – electron collision, can be calculated as follow:

$$E_{CE} = \frac{2E^2}{m_e c^2 + 2E}$$

The two Compton Edge of the 511 and 1275 keV photons correspond to 340 and 1062 keV, respectively.

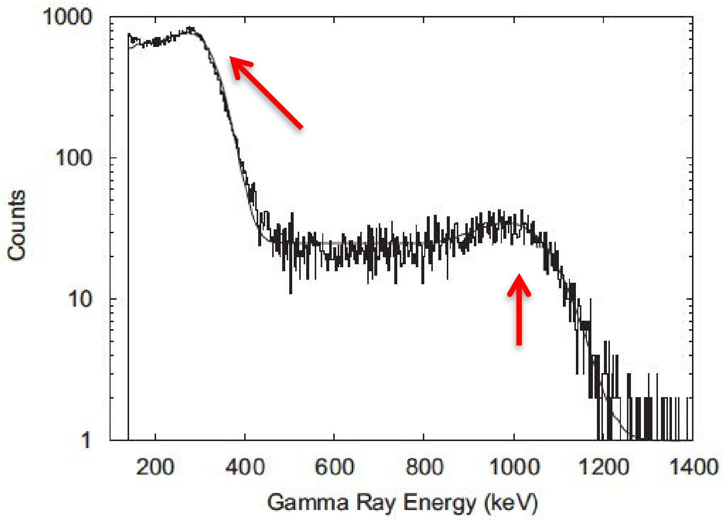


Fig.10.7: Typical spectra of ^{22}Na source measured with organic scintillators. The arrows show the Compton Edge of the 511 e 1275 keV photons.

The finite pulse resolution of the scintillation detector implies that the position of the maximum in the Compton events distribution is shifted toward lower energies, with the shift depending on the detector resolution. As a consequence it is not possible to simply measure the position of the Compton Edge and use it to obtain a calibration. Instead some empirical prescriptions have been developed in the past and simulations by Monte Carlo methods are commonly used to determine the shift value by fitting the experimental distribution [Stevanato et al. Appl. Rad. And Isotopes, Volume 69, 2011]. The overall pulse height resolution of the detector was reproduced by a Gaussian smearing of the predicted distribution (Kudomi, 1999; Siciliano et al., 2008). As an example, the effect of the Gaussian smearing corresponding to width values of σ= 5, 10, 15 and 25 keV is compared in Fig. 10.8 with the theoretical distribution. It appears, as expected, that the maximum in the Compton distribution moves toward lower energy values as the pulse height resolution decreases.

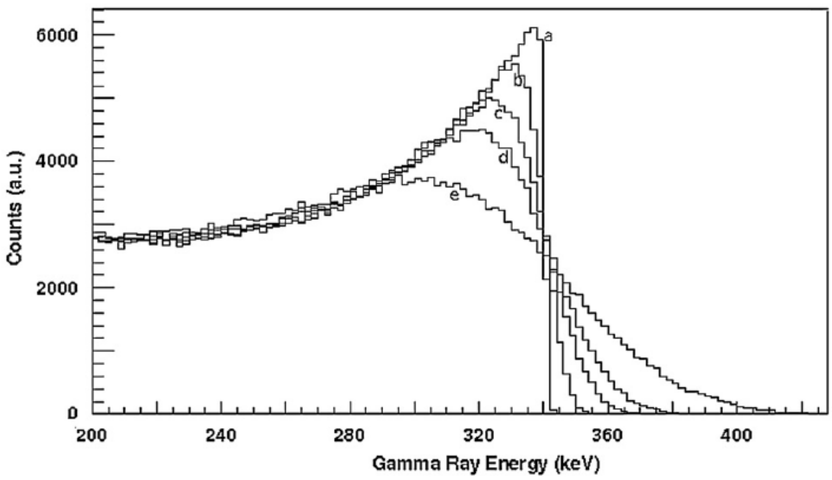


Fig.10.8: Computed distributions of the Compton scattered events without (a) and with different Gaussian smearing corresponding to 5 (b), 10 (c), 15 (d) and 25 (e) keV pulse resolution.

Starting from experimental spectra it is possible to fit the Compton edge with a Gaussian function as show in fig. 10.9.

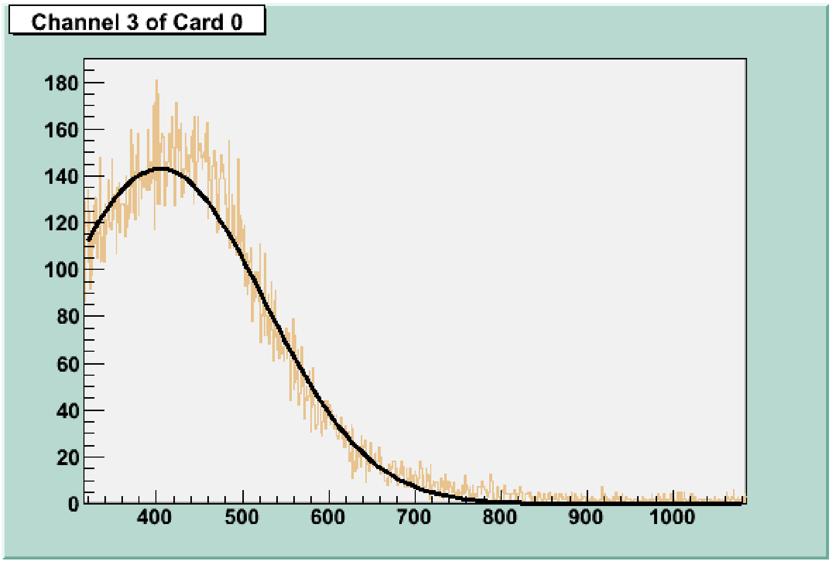


Fig.10.9: Gaussian fit of the Compton Edge

From the Gaussian fit you will obtain the centroid (C) and the sigma (•) of the edge, expressed in channels. With these two values you can directly calculate the parameter • • C. By means of response functions calculated as those in Fig. 10.8, it is possible to empirically correlate the value of the parameter • • C with the sigma value calibrated in keV as shown in Fig. 10.10a (511 keV) and 10.10b (1275 keV). Once you have determined the calibrated value of sigma, using Fig. 10.11a (511 keV) and 10.11b (1275 keV) you can empirically determine the corresponding shift value of the maximum of Compton edge. By this way, it is possible to obtain a simple estimation of the Compton edge shift respect to the nominal position in the gamma spectrum. Finally, you can calibrate the spectrum with a two points linear fit using the corrected values of Compton edge position.

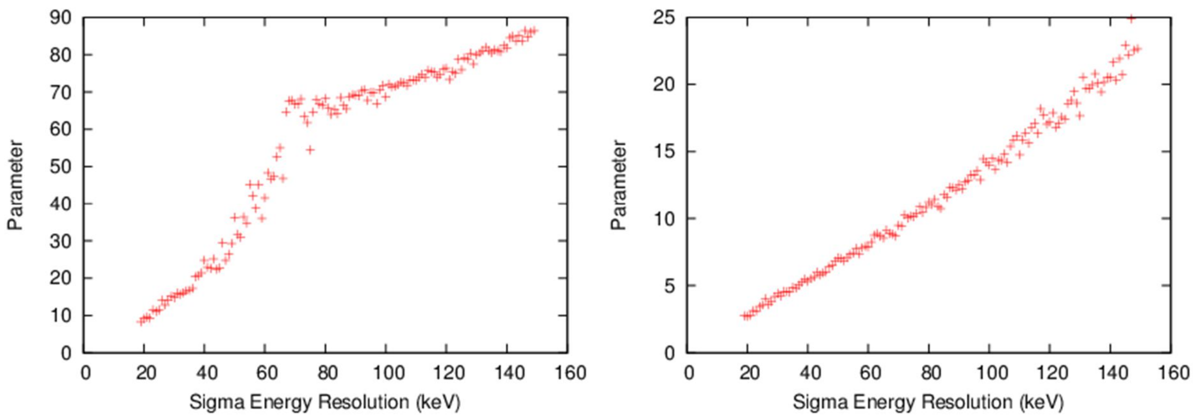


Fig. 10.10: Correlation between the parameter • • C and sigma in keV. a) left panel: 511 keV photon. b) right panel: 1275 keV photon. For details see the text.

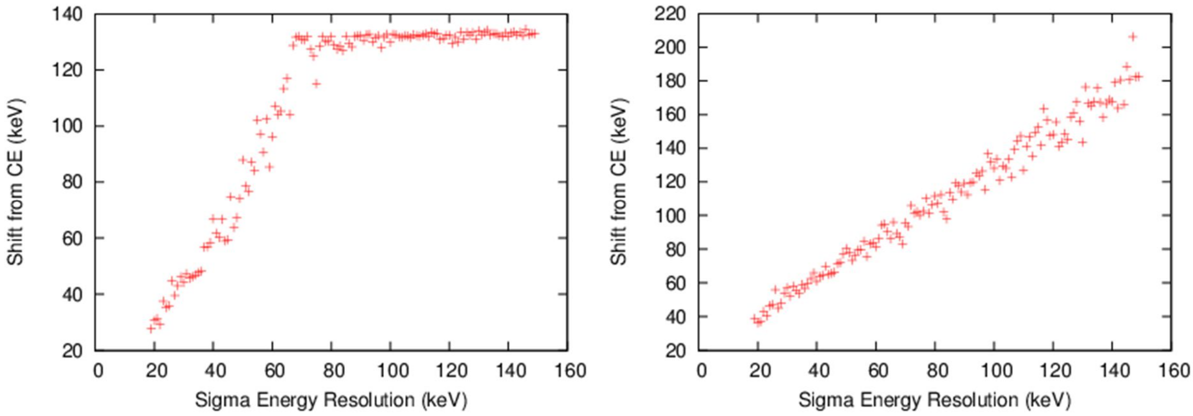


Fig. 10.11: Correlation between sigma value in keV, obtained from fig 10.10, and the shift of the Compton edge. a) left panel: 511 keV photon. b) right panel: 1275 keV photon. For details see the text.

10.3 Timing measurement with Digitizer DT5751

The goal of the last part of the experiment is a comparison between the results from timing measurement using an analogue chain based on CFTD and TAC and using a digitizer. In addition to the charge value, for each signal in this part of the experiment the waveform will be transferred and stored on the file root. You can use this data to build yourself an algorithm for a digital constant fraction time discriminator.

You will be given a root macro to read the data saved by VERDI. Within the macro there is a function to read the waveform and integrate the total charge as explained in Chapter 12. This allows you to compare the results of the online integration algorithm (qlong given by internal FPGA) with an integration done offline directly from the waveform. This procedure is useful to make you familiar with raw waveform from digitizer and to check if you are using it properly.

As in the analogue chain, in order to obtain the digital CFTD you have to split the signal, delay the first one of a quantity D and sum it to the second signal inverted and attenuated by a fraction F. You will get a bipolar signal as in fig. 10.11a. The zero crossing of the signal will be your time reference. Now you have to sum up the timestamp given by digitizer with the zero cross point to obtain the absolute time of the event, pay attention to the units. Finally, to have a time measurement, like in the TAC module, you have to make the difference between the absolute time of two coincidence events. The result is a time resolution graph, as in the right side of Figure 10.11.

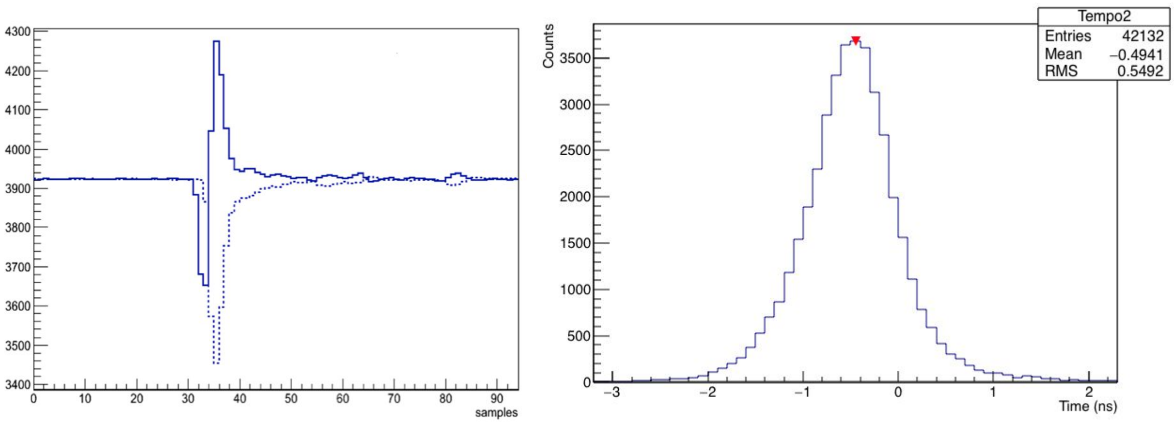


Fig 10.11: Left panel: example of digital CFTD. Right panel: digital time resolution spectra.

The parameters that optimize temporal resolution can be studied as in the analogue case. You will have to optimize the fraction F and the delay D to find out what are the two values that minimize

FWHM of digital CFTD. Then you can compare them to the results you obtained with the analogue chain.

Note: The Zero crossing is always to be taken with respect to a baseline amplitude value. In our case the baseline is not 0 but it is between the channels 900 and 1000. To find the zero crossing (or baseline crossing) it is recommended to interpolate a straight line for the two bin above and below the baseline value and then calculate the crossing value with this straight line. More complex treatments and interpolation functions can be tested for comparison. The digitizer samples every 1 ns, so the waveform values saved in the root file have a bin width of 1 ns.

10.4 Experimental protocol

The purpose of the timing experiment is:

a) Energy calibration of the organic scintillator and calculation of the energy resolution from the analysis of the Compton edge
b) Optimization of the external delay of analogue CFTD to obtain the best time resolution
c) Study the time resolution behaviour as a function of the energy range of the events
d) Measurement of the speed of light
e) Comparison between timing resolutions obtained from analogue and digital treatment of the signals

You will find the ^{22}Na source already inserted in the collimator.
You will find the detectors in operation with set appropriate HV values. During the experience you do not need to modify these values.

Initial operation

1) Connect the D#1 detector signal directly from the FAN-IN-FAN-OUT to the oscilloscope: write down the polarity, amplitude and signal rise time. Identify on the oscilloscope the amplitude corresponding to the full-energy peaks of the 511 keV and 1275 keV transitions.
2) Repeat the procedure for detector D#2.
3) You will find a pre-set delay into the two sections of CFTD. Now you have to set the CFTD threshold. The CFTD provides an output signal only if the input signal amplitude is greater than a V_{th} threshold value. The discrimination threshold is used to prevent the CFTD from operating triggering on the white noise of the electronics. Connect the anode signal to the oscilloscope from the FAN-IN-FAN-OUT and one of the outputs of the CFTD, triggering on the latter signal. Depending on the threshold value (set via the special trimmer that can be adjusted using the screwdriver) it is possible to check how the anode signal distribution changes, with the disappearance of the corresponding noise signals and low energy signals. Fix the threshold to the minimum value that is needed to cut the noise of the electronics.
4) Repeat the operation for detector D#2
5) Search for the coincidences. Connect the output of the D#1 CFTD to the channel 1 of the oscilloscope and trigger it on this signal. Connect the output of the CFTD of the DETECTOR #2 to a delay unit and then to the channel 2 of the oscilloscope. Check that the two signals have some timing overlap. To obtain the overlap, if needed, modify the delay on Delay Unit thought the switches. Make sure that the CFTD signal of D#2 is delayed of about 20ns respect to D#1. This ensures the correct operation of the coincidence unit. Connect cable to section 1 of coincidence Unit. The output of Coincidence unit is connected to the TRG IN of the digitizer and can work in AND or OR coincidence mode.

6) CFTD outputs are connected to the TAC. D#1 is the start and D#2, after DELAY UNIT, is connected to the STOP. The range of the TAC is pre-fixed at a value of 1 microsecond.
7) Start the acquisition system and verify what happens if you select OR or AND mode in coincidence UNIT.

Energy Calibration

The aim of this part of the experience is to acquire spectra for the energy calibration of the detectors. Remember to follow the hint given at the end of par 10.2.
For a more precise calibration, it is necessary to remove the coincidence condition in order to have a second CE in the spectrum, due to the 1275 keV photon.
Disconnect D#2 from coincidence unit and select OR from the switch. Acquire 15 minutes spectra. If you have done all right you can see on CH0 for detector D#1 the structures of the two CE.
Reconnect D#2 to the coincidence unit and disconnect D#1. Repeat the operation to obtain the calibration spectra of D#2 on CH1.
Reconnect D#1 to the coincidence unit and select AND with the switch.

Calibration of the TAC and calibration of the delay cable.

The aim of this part of the experience is to obtain a time calibration of the TAC spectrum acquired in CH2 and to measure the delay of the cable that you will use in the CFTD.
You will find the range of the TAC set to 1 microsecond. Register TAC spectra with delay between +2 and +30 ns, use different combination of switches of DELAY unit to have several points for the calibration. Calculate the centroid of each peak with a Gaussian fit and associate it to the delay used in the DELAY Unit. Make a linear fit to obtain the calibration (ns/channel).
You have a set of LEMO wires of different lengths. Set a delay of 8 ns in the DELAY UNIT. Add each cable, on at time, in series to the one that connects the delay unit with the STOP of the TAC. Acquire the spectra and find the peak position by Gaussian fit.
Using the calibration ns/channel obtained previously, you can calculate the delay introduced by the cable. Write down the data on the logbook.

Time resolution in function of external delay of CFTD

The purpose of this part of the experience is to verify the dependence of time resolution on the value of CFTD external delay.
Observing into the oscilloscope the anode signal of the detectors. If the downtime of the signal is about 5 ns, this implies that the optimum delay should be 4 ns, since the fraction of CFTD is fV = 20%. In the previous point you have measured the delay of LEMO cables so now you can choose the best cable for CFTD delay. Insert the cable into the two used CFTD sections. You can now look at the CF MONITOR signal that is the bipolar signal created by the CFTD.

1) Connect the CFTD output of D#1 to the oscilloscope and use this signal as a trigger. Connect to the second channel of the oscilloscope the CF MONITOR. Look the bipolar signal produced by CFTD as show in Fig. 10.12

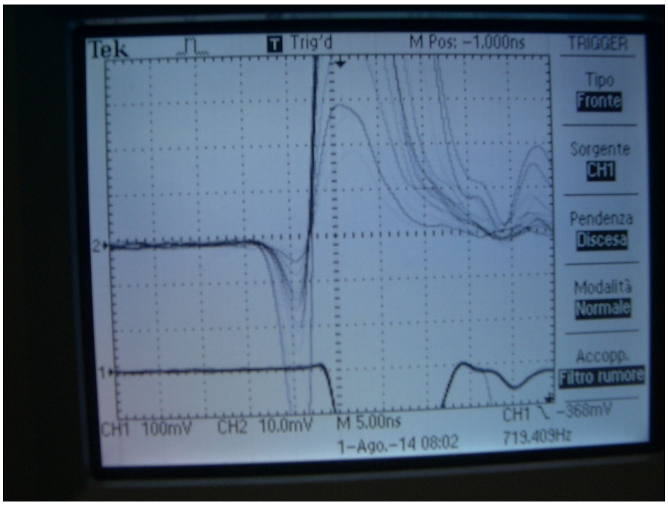


Fig.10.12 Bipolar signal produced by CFTD

2) By adjusting the WALK ADJ (Z) potentiometer, you can move the zero crossing point (the zero crossing is used to generate the CFTD output signal) to minimize dispersion as shown in fig 10.12.
3) Repeat points 1 and 2 for D#2.
4) Register a file for 10 minutes and measure the time resolution of the peak by a Gaussian fit.
5) Add and subtract 1 ns in the external delay of CFTD. Repeat points 1-4. Remember to check and adjust the WALK ADJ if needed
6) Compare the sigma values obtained for the three delays by defining which minimizes the time resolution. If the trend is not clear, continue the study with one or more delays.

Measurement of time resolution in function of energy range. (Night measurement between second and third day)

Check if the system is set correctly with the optimal values of the two CFTDs (thresholds and WALK ADJ). You can take data during the night between the second and third day. You will use this data to extract the time resolution for an increasing energy thresholds and different energy windows. For this measurement ask the lab personnel to replace the ^{22}Na source with a ^{60}Co source. The ^{60}Co decades with two non-collinear photons of 1.17 and 1.33 MeV, see Chapter 11. A small percentage of these decays also occur at 180° angles allowing you to measure a coincidence as for the ^{22}Na. The advantage of using the ^{60}Co is to have the CE at about 1 MeV and therefore you are able to study the time resolution in function of the energy threshold up to 1 MeV. After you have saved the file, ask the lab personnel to replace the source with ^{22}Na.

Measurement of the speed of light

The detectors are positioned on a slide that allows them to move on a length of about 2 meters. We know that the gamma rays emitted by the source travel at the speed of light c = 299792 km/s. The aim of this part of the experience is to measure this quantity.

1) Check if the system is set correctly with the optimal values of the two CFTDs (thresholds and WALK ADJ).
2) Arrange the lead collimator with ^{22}Na source near D#1. Ask to the lab personnel to do this operation.
3) Connect CFTD of D#1 to the channel 1 of the oscilloscope and use it as a trigger. Connect CFTD of D#2 to the second channel of the oscilloscope and check the coincidences. Verify

that the widths of the signals are about 150 ns and that the delay between the two signals is 40 ns. If not, modify properly the DELAY UNIT and CFTD widths.

4) Write down the distance between the two detectors and the source position
5) Acquire for one hour using the pre-set time function of the VERDI interface.
6) Ask that the source is moved close to D#2 and acquire a second run lasting for 1h.

Calibrate in time the spectra with the TAC calibration obtained the previous day. With a Gaussian fit calculate the centroid and the sigma of the peaks in seconds T_1 (source near D#1) e T_2 (source near D#2). Calculate the speed of light as follow:

$$c = \frac{D}{T_1 - T_2}$$

where D is the distance between the two detectors. Propagate errors and discuss the results.

Measurement of the time resolution obtainable by means of a digital CFTD

Ask to the lab personnel to reposition the detector in original position (close packing of source and detectors) and to change the configuration file for VERDI. Disconnect the TAC from digitizer. Acquire for the remaining time (recommended almost 1h) a file in coincidence with ^{22}Na source to reproduce offline the digital CFTD. Discuss and compare the results.

Timing Experiment Log file

Group...........   Padova..........................

SET UP of DETECTORs

Characteristics of the anode signals terminated at 50 Ohms

DETECTOR	Fall Time (ns)	Vmax @511 keV (mV)	Rise Time (ns)	Noise Level (mV)
#1				
#2				

Time Calibration of the TAC

Delay	Centroid (Channel)	Sigma (Channel)
4 ns		

TAC calibration: ……..ps/channel

Delay	Centroid (Channel)	Sigma (Channel)
30 ns		
30 ns + LEMO cable 10 cm		
30 ns + LEMO cable 20 cm		
30 ns + LEMO cable 50 cm		

LEMO Delay (ns)	Centroid (Channel)	Sigma (Channel)	Time Resolution [FWHM] ns

TAC calibration: ……..ps/channel

HINTS FOR DATA ANALYSIS

Many of the data of this experience will be analysed directly at the lab. However, it is suggested to save the data to a file in order to repeat the analysis .

For the analysis of the time resolution as a function of the energy range, we suggest:

a) Calibrate in energy the spectra.
b) Set a lower energy threshold in both detectors from 100 to 1000 keV with step of 50 or 100 keV. With this condition on energy calculate the time resolution in TAC spectrum and plot it in function of lower energy threshold.
c) Repeat the previous points setting an energy window: [50-150 keV], [250-350 keV], … , [850-950 keV].
d) Comment the results of point b and c.

Measurement of the speed of light:

e) Why do we use this procedure to measure the speed of light?
f) Propagate and discuss in details the errors in the measure

Measurement with the digitizer:

g) Comment the structure of a waveform, falltime, rise time, pulse height (the acceptance of the digitizer is 1 volt). Calculate the mean falltime of the signal using the last measurement for digital CFTD. Compare the results with oscilloscope measurement.
h) Create an energy spectra using the waveform. Compare with the energy spectra obtained directly from the FPGA stored in QLONG.
i) Optimize CFTD parameter D and F. Vary the delay D between 1 and 10 bin and the fraction F between 0.1 e 0.9.
j) With the optimal CFTD value D and F, study the time resolution in function of lower energy threshold as point b. Now you have the data from the ^{22}Na source, so you cannot operate with a threshold larger than 300 keV.
k) Compare the time resolution obtained from the TAC and the digitizer.