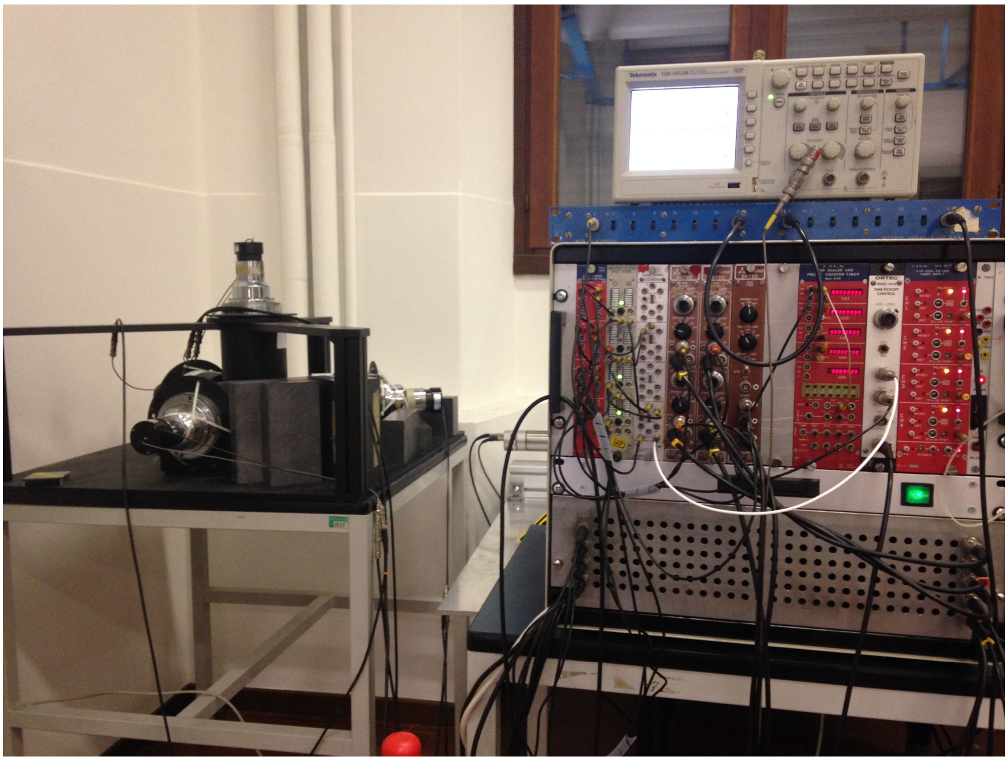
Chapter 8

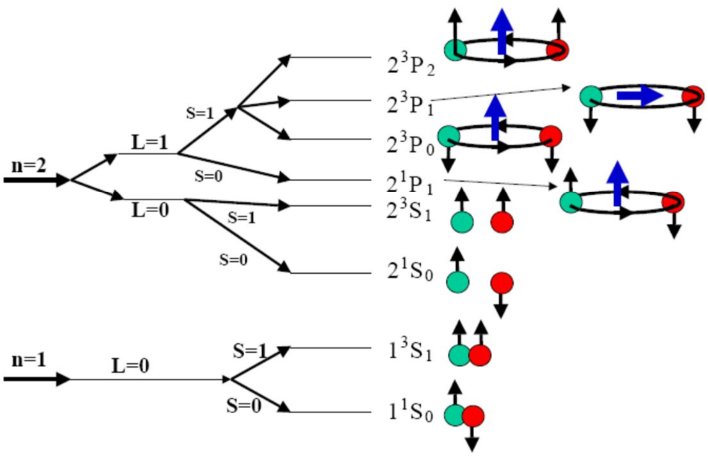
Experiment # 6

Study of the Positronium annihilation



8.1 Introduction

When a positron annihilates with an electron, two photons of 511 keV are produced collinearly. The two photons decay-channel is not the only allowed mode of annihilation, in fact multiple photon emission is possible (three or higher). However, the probability of decay decreases as the number of photons increases. In fact only the three-photon decay-channel has been studied in detail, while the channels involving the emission of 4 or 5 photons have an incredibly small probability.
Ore & Powell estimated the ratio between two and three photons decay channel in 1949 [Phys. Rev. 75 (1949) A696]. They found a value of 1/373. Furthermore experimental measurement done by DeBenedetti & Siegel few years later [Phys. Rev.94 (1954) 955] have confirmed the dependence of the three photons decay-channel on the type of material in which the positron slow down and annihilates.
In a material the positron can bind with an electron, thus forming a bound state with a short lifetime called Positronium (Ps). One-fourth of the positronium atoms are formed in the state of singlet S = 0 (see Figure 8.1), creating what is called para-positronium (p-Ps), and 3/4 are formed in the triplet state S = 1, called ortho-positronium (o-Ps). If we consider the two states o-Ps and p-Ps they can decay with the emission of 3 photons and 2 photons, respectively. The lifetimes are 142 ns (o-Ps) and 0.125 ns (p-Ps).



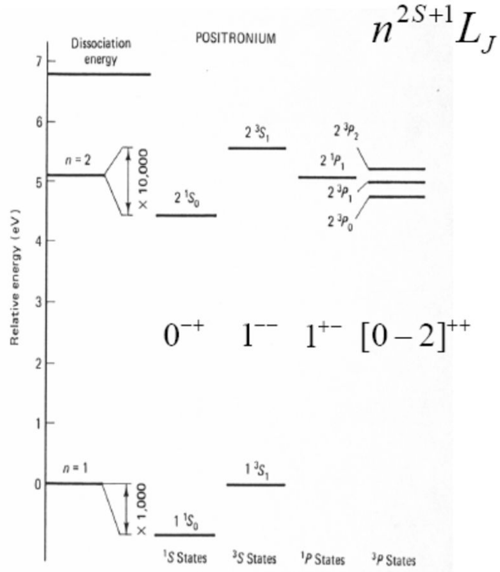


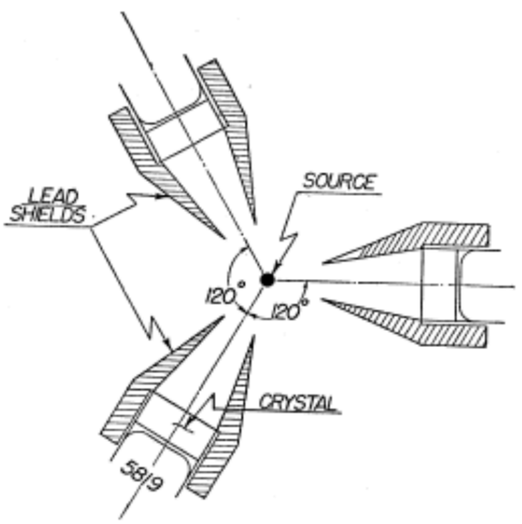
Fig. 8.1 Possible positronium bound states

Once the states of o-Ps and p-Ps are formed in the materials, atomic processes convert part of the o-Ps in p-Ps. Such processes are depends on the structure of the material itself and are governed by the atom kinetics. As a consequence of the conversion of part of the o-Ps into p-Ps the ratios measured between three and two photons decay changes. As an example we show in Table 8.1 the yield of the 3-channel decay for different materials in relation to the one measured for Aluminium. Due to this dependence, positron annihilation is used to study the structure and composition of the materials.

Z	Metal	R
4	Be	0.94±0.04
23	V	1.01±0.03
26	Fe	0.98±0.03
28	Ni	1.14±0.03
29	Cu	0.98±0.04
30	Zn	1.04±0.03
42	Mo	1.05±0.03
46	Pd	0.99±0.04
47	Ag	1.13±0.02
48	Cd	1.10±0.04
74	W	1.02±0.03
77	Ir	1.06±0.04
78	Pt	1.16±0.04
79	Au	1.04±0.03
82	Pb	1.16±0.03

Tabella 8.1: Experimental data from Bertolaccini et al., (Phys. Rev. 139 (1965) A696). R is the ratio of the three decay-channel in different material respect to one measured for an aluminium sample.

From an experimental point of view, the setup used to study positronium is typically a set of inorganic scintillator detectors working in coincidence. They measure the simultaneous arrival of the two (or three) photons emitted by the positronium.
Fig. 8.2 shows the experimental setup used by DeBenedetti & Siegel and the typical energy spectra obtained at different angular positions of the detectors.



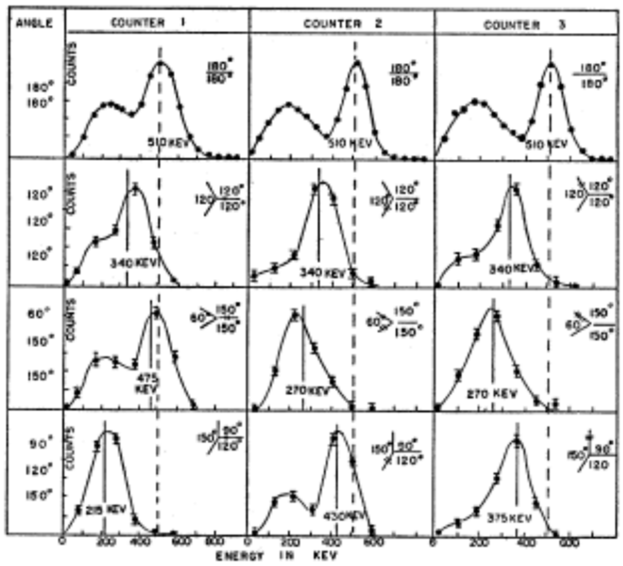


Fig.8.2 Experimental setup used for the study of Positronium decay (left). Energy spectra measured at different angles (right).

It is important to notice that the positronium annihilation happens essentially at rest. Consequently, the linear momentum in the input channel of the reaction is negligible and therefore the total linear momentum in the final state, i.e. the sum of the moments of the two (or three photons), must be null. The conservation of the linear momentum implies collinearity in the case of decay by two photons and implies complanarity in the case of decay by three photons. In the latter case, the energy of the photons in the final state depends on the emission angles as shown by the experimental results reported in Figure 8.2. Particularly interesting is the case where the three detectors are in a symmetrical configuration, with a 120° angles in between them. In this case the three photons are expected to have the same energy, corresponding to one third of the total, i.e. about 340 keV.

Other experiments (see, for example, McGervey et al., Phys. Rev. B7 (1970) 2421) have been dedicated to the temporal characterization of the decay in different materials. As an example we show in Fig. 8.3 the temporal distribution of the positronium decay in Teflon material. The short and long life components are clearly distinguished.

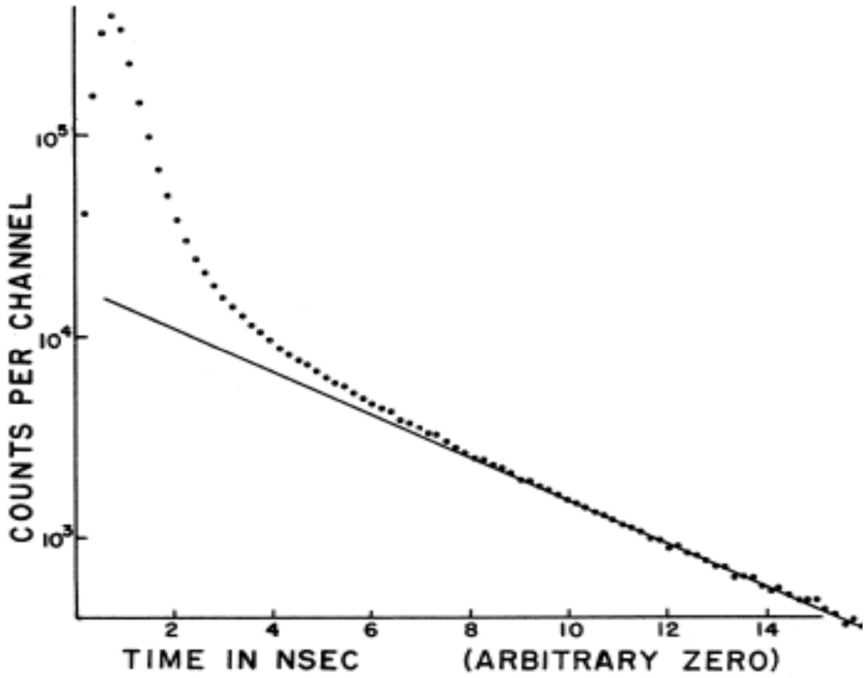


Fig. 8.3 Temporal distribution of the decay of Ps. The continuous line is a fit on the part dominated by long lifetime state.

8.2 Experimental setup

The aim of this experiment is:

1) To verify the ratio between the decay in two and three photons of the positronium;
2) To measure the temporal distribution of the events

A ^{22}Na source is placed in the middle of the experimental setup. The setup is made of:

a) An inorganic NaI(Tl) detector mounted vertically over the source (Detector#4);
b) A three arms goniometer in which the other three NaI(Tl) inorganic detectors are mounted (Detectors #1,#2,#3).

If we define with $\Delta\Theta_{12}$,$\Delta\Theta_{13}$,$\Delta\Theta_{23}$ the angle between the detector #1 , #2 e #3 respectively, the two geometric configuration of our interest will be:

1) $\Delta\Theta_{12} = \Delta\Theta_{13} = \Delta\Theta_{23} = 120^o$ for the study of three photons decay channel
2) $\Delta\Theta_{12} = 180^o$ $\Delta\Theta_{13} = 120^o$ $\Delta\Theta_{23} = 60^o$ for the study of two photons decay channel between the detector #1 e #2.

All the detectors used in this experiment are NaI(Tl) detector. Their shape correspiond to an active cylinder of 10 cm diameter and 10 cm length, inserted into a lead collimator. The detailed description of the detectors together with additional information about gamma spectroscopy is reported in Chapter 12.
Concerning the electronics used in this experiment we can notice:

1) The PMT takes the HV from a Power Supply CAEN N472 that provides 4 independent channels. You will already find the detectors in operation with appropriate HV values set.
2) The PMT of each detector provide a fast anode signal.
3) The anode signal is sent as an input to a Quad Linear Fan-in Fan-Out CAEN 401 for signal splitting (function fan-out). This module can replicate the signal without modifying its characteristics (pulse height, rise time, decay time). The first signal is connected to the input of a Constant Fraction Timing Discriminator module, CFTD (for detailed description of CFTD see chapter 12 e chapter 4.2.2). The second signal will be inserted directly into the acquisition system: a CAEN digitizer mod. DT5720, see Chapter 12.4 for details on the Digital Electronics and Appendix V for the DAQ system.
4) The CFTD provides two types of output signals, a prompt signal, and a delayed signal, of which it is possible to vary both the duration (WIDTH) and the delay by microswitches. The possibility of adjusting the logic signal duration and delay is extremely useful for making a coincidence overlap between the various detectors (see Chap. 3). The module used for the coincidences is a Quad Coincidence Unit ESN mod. CO4000. The output of logic unit module is NIM standard (-800 mV) and can be used as a MASTER TRIGGER by the digitizer.
5) In order to measure the temporal distribution of the positronium decay respect to the decay of ^{22}Na you will use a Time To Amplitude Converter (TAC). For the description of TAC see Chap. 12.
6) The second output of the fan-out is connected directly to a CAEN digitizer DT5720 with a sampling rate of 250 Ms/s and a resolution of 12 bit. The digitizer can perform online analysis thanks to an internal FPGA. It provides for each event the total integral of the signal (proportional to photon energy) and a reference timestamp of the event referred to the start of the acquisition. See Chapter 12.4 for details on the Digital Electronics and Appendix V for the DAQ system

The electronic diagram is shown in Fig. 8.4.

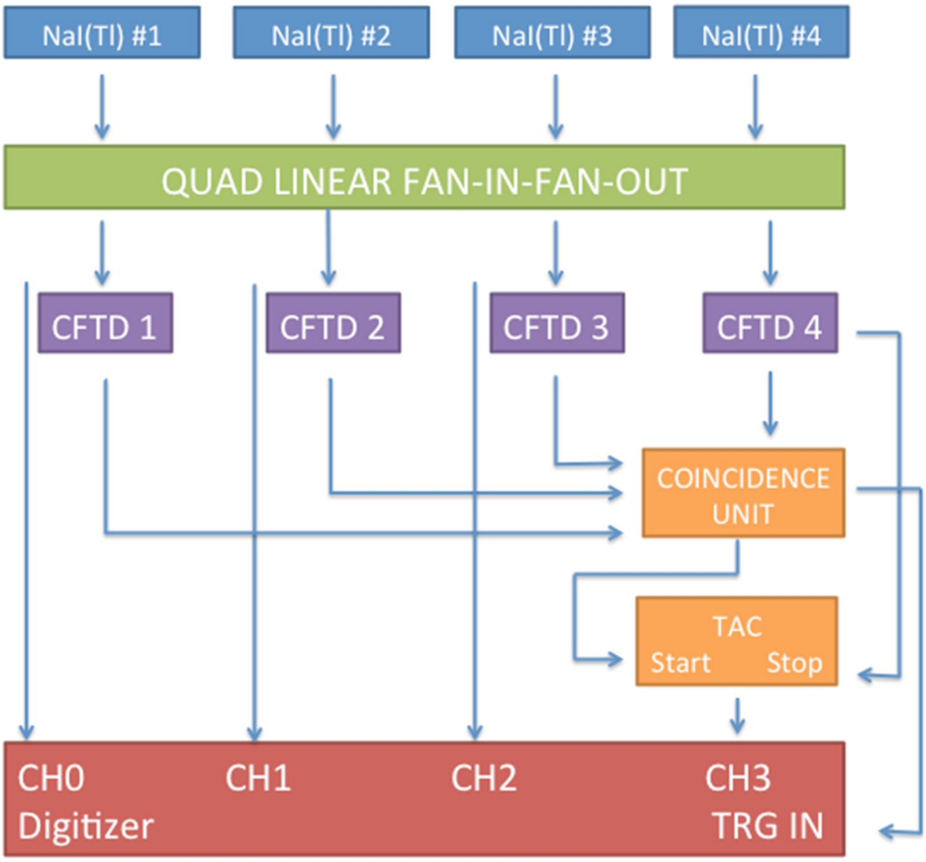


Fig. 8.4 Electronic schematic for Positronium experiment

8.3 Experimental protocol

As already mentioned, the purpose of the experiment on Positronium annihilation is:

1. To verify the ratio between the decay in two and three photons of the positronium;
2. To measure the temporal distribution of the events

The experimental protocol is subdivided into the three sessions available for the experiment. The timing chart below is can be varied by students also in relation to issues or further investigations stimulated during the laboratory sessions.

3.5 First session: preparation and calibration of the scintillators

You will find the ^{22}Na source already inserted into the support in the middle of the three coplanar NaI(Tl). The detectors are already in operation with appropriate HV values.

1) Connect the anode signal of the detector in vertical position over the source (DETECTOR # 4) directly to the oscilloscope. Look at the signal and write down the polarity amplitude and signal rising time. Now connect the anode signal to the input of FAN-IN-FAN-OUT and check the output in the oscilloscope. Identify on the oscilloscope the amplitude corresponding to the full-energy peaks of the 511 keV and 1275 keV transitions.
2) Connect the second output of the FAN-IN / OUT to the CFTD input and send the CFTD output prompt signal to the oscilloscope and observe it. By triggering the output signal prompt, connect the output signal of CFTD to the second oscilloscope channel and observe it. Understand the effect of the operation of the micro switches for different *width* and *delay* values.

3) Setting of 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 on the white noise of the electronics. In this experiment relatively low energies will be measured in case of photons detected on the plane (DETECTOR #1,2,3) otherwise the threshold of the detector in vertical position (DETECTOR #4) must be set at higher value in order to trigger only in case of a 1275 keV photons. It is therefore particularly important to verify the values of the threshold of discrimination.
To do this, proceed as follows: 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 (DETECTORE #1,#2,#3) and at the minimum value to cut 511 keV events for DETECTOR #4
4) Connect the anode signal from the FAN-IN-FAN-OUT of the detector to input #1 of the data acquisition. Connect the delayed output (with minimum delay) directly into the TRG IN of the digitizer. Connect the CFTD prompt output to the CAEN scaler to verify the counting speed.
You are now ready to record the source spectrum of ^{22}Na. Verify that in the spectrum the peak at 511 keV lies around the channel number 7500. Acquire the spectrum and record it as a file. For DETECTOR #4, first use the threshold at minimum in order to have two peaks for calibration, then set again the threshold at the correct value for cutting 511 keV events. Save the file and verify the energy of the cut. Since in the spectrum of ^{22}Na there are two peaks, you can determine the centroids by a Gaussian fit and then obtain the spectrum calibration:

$$E_\gamma = a + b \cdot N_{canale}$$

Typical example of spectra obtained in the laboratory is shown in Fig. 8.5.

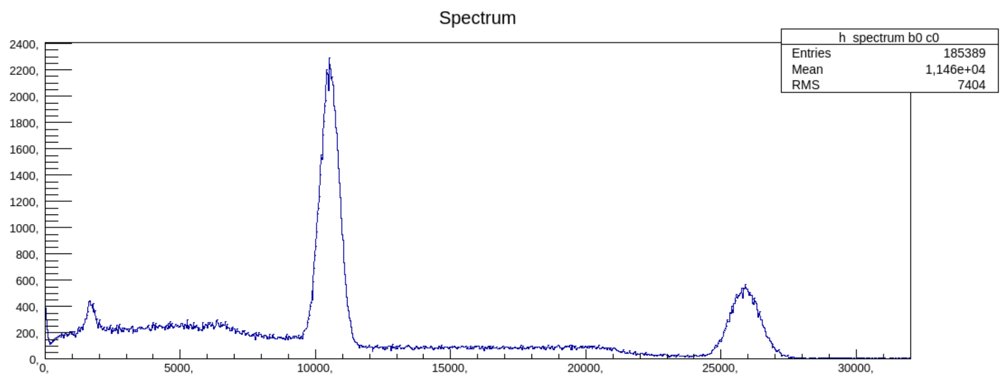


Fig. 8.5 Typical energy spectra with the source of ^{22}Na.

5) Repeat steps 1-4 for the other detectors sitting in the plane (DETECTOR #1 #2 e #3).

8.4 Second session: search for the coincidences and temporal distribution of the events

Search for the coincidences. In order to check that the CFDs' "delayed output" signals of the four detectors have an overlapping region, use the following procedure:

1) Adjust the width of the three (DETECTOR #1,#2,#3) CFTDs delayed signals to the value W = 100 ns using the oscilloscope and set the minimum delay.
2) Verify the geometry of the detectors in the plane: $\Delta\Theta_{12} = 180^o$ $\Delta\Theta_{13} = 120^o$ $\Delta\Theta_{23} = 60^o$ (i.e. DETECTOR #1 and DETECTOR #2 collinear). If the detectors are not in the right position, ask to laboratory personnel to move the detectors. Connect the delayed output of the DETECTOR #1 CFTD to the channel 1 of the oscilloscope and trigger it on this signal. Connect the delayed output of the CFTD of the DETECTOR #2 to the channel 2 of the oscilloscope. Check that the two signals have some timing overlap. To obtain the overlap, if needed, modify the two CFTD delay (with the micro switches). Make sure that The CFTD signal of DETECTOR #2 is delayed of about 20 ns with respect to DETECTOR #1. This ensures the proper settings of the coincidence unit.
3) With the same geometry: $\Delta\Theta_{13} = 120^o$ (i.e. DETECTOR #1 and DETECTOR #3 not collinear). Keep the delayed CFTD signal of DETECTOR #1 as a trigger and connect delay output of CFTD of DETECTOR #3 to the channel 2 of the oscilloscope. You can see few coincidences between two detectors. Check that the two signals have some timing overlap, , if needed, modify the two CFTD delay. Now you have checked the coincidences between the three detectors on the plane.
4) You will find the output delayed of the CFTD connected to the Coincidence Unit as the following scheme:

Section	Channel	Detector	Comments
I	A	D1	
	B	D2	Coincidences between two collinear detectors
	C	----	
II	A	D1	
	B	D2	
	C	D3	Coincidences between three detectors in the plane

Verify that the detectors on the plane are in the geometry configuration

$$\Delta\Theta_{12} = 180^o \quad \Delta\Theta_{13} = 120^o \quad \Delta\Theta_{23} = 60^o$$

Check the connection to CH0, CH1, CH2 of the digitizer to DETECTOR #1,2,3 from FAN-OUT. Connect the output of section I of Coincidence Units (Coincidences between collinear detector) to the TGR IN of digitizer. You are now ready to take data in coincidences between DETECTOR #1 and #2. Start the acquisition system and verify that the spectra obtained in this first acquisition are correct.
5) After you have checked the correctness of the first acquisition, you must set the electronic part to measure the temporal correlation between the decay of ^{22}Na (i.e. emission of the positronium) and the characteristic event of the positronium decay: the emission of two or three gamma-ray.
The temporal distribution between the two events are measured by a Time to Amplitude Converter (TAC), you can find more details about TAC in chap 12. Briefly TAC generates an output proportional to the delay between the "START" and "STOP" signal. In our case we will use the PROMPT CFTD output of the DETECTOR # 4 as START signal (^{22}Na decay) and

output of the Coincidence Unit as a STOP (Ps decay). Use the right output of the coincidence module (sections I or II) based on the decay of interest (coincidence for two or three PS photons decays). Take care to check if the Delay Unit placed before the STOP is set to zero delay. The delay unit will be used to calibrate the TAC (see section 4.2.3). Connect the TAC output signal to CH3 of the digitizer. The range of the TAC might is one of the free parameters that might need to be adjusted.
7) Acquire a second file to check if everything is correct. Verify the presence of the coincidences peak in CH3. If everything works correctly, calibrate the TAC by inserting different delays in the Delay Unit and recording the peak shift of CH3. Once the TAC calibration is complete, you are ready to make the final measurements.

8.5 Second – third session: data taking.

Once the preparation of the experimental setup has been completed, two datasets corresponding to the two geometries must be taken:

1) $\Delta\Theta_{12} = 180°$ $\Delta\Theta_{13} = 120°$ $\Delta\Theta_{23} = 60°$ for the study of positronium decay in two photons between detector #1 and #2.
2) $\Delta\Theta_{12} = \Delta\Theta_{13} = \Delta\Theta_{23} = 120°$ for the study of three-photons decay

You already know a priori that the probability of three-photon decay is two orders of magnitude lower than two-photon decay. Use the time available in the most appropriate way. We recommend the following procedures:
1) Measurement at $\Delta\Theta_{12} = 180°$: master trigger for acquisition (D1.and.D2); stop signal for the TAC : (D1.and.D2).
2) Measurement at $\Delta\Theta_{12} = \Delta\Theta_{13} = \Delta\Theta_{23} = 120°$: master trigger and stop for the TAC: D1.and.D2.andD3. The "net" three-photon events will be those where a valid TAC signal has been measured and can be reconstructed via software selecting proper window on CH3 of the digitizer.
The three-photon decay data acquisition takes long time so you normally acquire in this configuration during the night between the second and third sessions (remember to write down acquisition time when you stop the acquisition!). However, the measurement of two-photon decay requires a much shorter time (60 minutes) and can be done either at the end of the second or during the third session.

The ^{22}Na source used in the experiment has an activity of about 380 kBq. In these condition the counting rate are high and you might have some problems regarding the dead time of the acquisition system.
We suggest the following procedure to check the problem:

a) Use the CAEN scaler module to verify the counting rate of the detectors and the counting rate of the coincidences. You can use a free output of the CFTD or a free output of coincidences unit. You can check these data during the acquisition.
b) You will find the lower section of the coincidence units already connected. You can set a coincidence between DETECTOR #4 and the coincidences (D1.and.D2) or (D1.and.D2.andD3).
c) For the two-photons coincidences take two files. The first using as MASTER TRG the coincidences (D1.and.D2) as descripted in previous points. Otherwise for the second file use the coincidences with DETECTOR #4: (D1.and.D2).and.D4, for this file you have to use the last section of COINCIDENCE UNIT. The comparison between the statistics in the two files will give you the possibility to check the dead time of the acquisition system.

d) You can check if the problem exist for the case of the coincidence with three photons. To this purpose you can set as MASTER TRG the coincidence between (D1.and.D2.andD3).and.D4.

8.6 Suggestions for the data analysis.

1) Calibrate the gamma spectra and TAC.
2) **Two-photons deacy**: Set a proper energy window for DETECTOR #1, #2 and proper temporal window for the TAC in order to reject uncorrelated events
3) Counts two photons events per unit of time.
4) **Three-photons deacy**: Set a proper energy window for DETECTOR #1, #2, #3 and proper temporal window for the TAC in order to reject uncorrelated events. Verify that the energy in case of three photons is in agreement with the theory.
5) Counts two photons events per unit of time.
6) Compare the counts per unit of time for two and three photon decay and determine the ratio. What are the roles of the geometry and of the efficiency of the detectors? Discuss the necessary corrections.
7) Compare the time spectra measured in the two experimental configurations.
8) For 2 and 3 photon decay, you can also build the sum spectra for energy. Comment and analyse it.
9) Check the dead time of the system and make any corrections to the results if needed.

Positronium 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				
#3				
#4				

DETECTOR	CFTD Threshold (Measured by the oscilloscope)	Rate (scaler) Hz
#1		
#2		
#3		
#4		

Energy Calibration

DETECTOR#1

Energy	Peak centroid (Channels)	Peak width [FWHM]	Resolution (%)
511 keV			
1275 keV			

Calibration (E= α x Channel + β) α=........................ β=.......................

DETECTOR #2

Energy	Peak centroid (Channels)	Peak width [FWHM]	Resolution (%)
511 keV			
1275 keV			

Calibration (E= α x Channel + β) α=........................ β=.......................

DETECTOR #3

Energy	Peak centroid (Channels)	Peak width [FWHM]	Resolution (%)
511 keV			
1275 keV			

Calibration (E= α x Channel + β) α=........................ β=.......................

DETECTOR #4

Energy	Peak centroid (Channels)	Peak width [FWHM]	Resolution (%)
511 keV			
1275 keV			

Calibration (E= α x Channel + β) α=........................ β=.......................

CFTD SET UP

DETECTOR	Width CFTD	Delay CFTD	Rate
#1			
#2			
#3			
#4			

Coincidences Rate (D1.and.D2):…………………c/s
Coincidences Rate (D1.and.D2.andD3):…………………c/s

TAC

Delay on the stop:………..ns

Calibration of the TAC

Delay (ns)	0 ns	4 ns	8 ns	16 ns	24 ns
Peak centroid (Channel)					

Calibration time/channel:......... ns/channel