Determining scintillation pulse shapes of fast PET scintillators

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Bachelor's thesis

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Abstract

Determining the scintillation pulse shapes of PET scintillation crystals, especially the rise time of the pulse, will yield valuable information for making choices in the design of time of flight-PET scanners, with respect to e.g. scintillator crystal material and the detector trigger schemes. This can eventually improve the image quality of PET scans by noise reduction and/or reduce the image acquisition time and the dose to the patient. Knowledge of the rise time of the scintillation pulse is also of great importance in the modelling of the physical processes involved in scintillations.

Several setups are presented and assessed with the intention to develop a procedure that is relatively easy to implement and is suitable for determining scintillation pulse shapes of PET scintillation crystals, excited by 511 keV photons, with sub-nanosecond timing resolution. The emphasis is on characterizing the rising edge of the scintillation pulse. The time correlated single photon counting method was employed in all of the setup variations.

A proof-of-principle of the applicability of a suitable measurement procedure is given, which achieves a timing resolution of 120 ps FWHM and was used to determine the exponential rise time of a lutetium-yttrium oxyorthosilicate (LYSO) scintillator to be 81 ps with an estimated uncertainty interval of [50,120] ps. Also recommendations for further work on the basis of this procedure are made.
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Introduction

History of Positron Emission Tomography

Beginning in the early 1980’s, Positron Emission Tomography (PET) came into play as a promising imaging technique in nuclear medicine to visualize biological processes. To date, PET is the most prominent biological imaging technique.[1]

In nuclear medical imaging a radioactive substance, the tracer, is administered to the patient and an image is acquired of the subsequent distribution of the tracer in the patient’s body or in a particular organ. In PET radiopharmaceuticals are used incorporating positron emitting isotopes like $^{18}$F, $^{15}$O, $^{11}$C or $^{13}$N. The principle of PET is based on the fact that an annihilation of a positron with an electron produces two 511 keV $\gamma$-photons travelling in diametrically opposed directions.[2] Scintillation detectors sensitive to these photons are placed in a ring around the patient, detecting two photons in coincidence. A line of response (LOR) between the interaction positions of the coincident photons in the scintillation crystal of their respective detector can be constructed, as depicted in figure 1, along which the positron-electron annihilation must have taken place. Using computed tomography, an image is finally reconstructed from many of these coincident events.

![Figure 1: PET setup, showing an annihilation event in the sample and detectors A and B detecting a coincident scintillation from which a LOR is constructed.](image)

PET is the most sensitive imaging modality for functional imaging. It is possible to track the concentrations of the tracer substance with sub-picomole sensitivity.[3] The used isotopes can be combined in compounds which have certain biological activity, so that the generated image reflects specific biological processes, like, for example, the metabolism of the heart and in the brain.[4] An important application of this functional imaging using PET is assessing the uptake of $^{18}$F-Fluorodeoxyglucose ($^{18}$F-FDG) in tumours. This is directly related to the metabolism of the tumour, providing a way to measure the response of a tumour to treatment like chemotherapy or radiotherapy.[5]

Another significant application of PET is to perform whole body scans for the detection and analysis of tumours with the ability to differentiate between benign and malignant tumours.[6]
Improving PET scanner performance

There have been recent developments of new scintillation detectors to improve the image quality in PET. Improving the spatial resolution of the detectors is an important objective. Various ways to achieve this have been investigated.

Depth-of-Interaction correction

One of the effects that degrade the image quality in PET scanners is the lack of depth-of-interaction (DOI) information. The DOI refers to the depth in the crystal at which the photon is absorbed. If the DOI is unknown there is an uncertainty in the position of the LOR due to parallax errors, resulting in a degradation of the spatial resolution, as illustrated in figure 2.

Figure 2: Illustration of the uncertainty in the LOR if the DOI is unknown. Scintillation crystals A and B detect coincident photons and four possible LORs are shown.

The degradation of the spatial resolution in the image can be reduced significantly, as described by MacDonald et al.[7] Different ways of acquiring the DOI information are described in literature. One possibility is to use segmented crystals, which are read out independently[8], another is using phoswich detectors, which consist of multiple layers of scintillators with different scintillation pulse shapes, stacked on top of each other. The difference in pulse shapes can be realized by a wide variety of methods, for instance by applying a temperature gradient across the crystal[9] or by using different scintillating materials in the different layers.[10] This difference in pulse shapes is used to determine the DOI by means of pulse shape discrimination.

An alternative way to reduce the parallax errors is to estimate the photon entry point rather than the point of interaction within the scintillation crystal.[11] Using detection of the scintillation light at the front of the crystal (front-side readout, FSR) is a way to improve entry point estimation with respect to conventional back-side read-out.[12]

Silicon Photomultipliers

Applying FSR is made possible by using light sensitive detectors other than photomultiplier tubes (PMTs), for instance silicon photomultipliers (SiPMs). This is a second field of development of PET. Besides the aforementioned advantage of the SiPMs, they are also compatible with magnetic resonance (MR) imaging (as opposed to PMTs), allowing the combination of PET and MR imaging in a single device. Furthermore SiPMs offer faster response and higher gain than other solid-state light detectors such as avalanche photodiodes (APDs).[13]

Time-of-Flight PET

The present work is mostly concerned with another recent development in PET technology, called time-of-flight (TOF) PET.[14] The basic principle of this added functionality is to measure the difference in the arrival times between two coincident photons at their respective detectors. Using this time difference, an estimate can be made approximately where on the LOR the annihilation event must have originated. Thereby the volume of the possible origin of the annihilation is reduced, increasing the amount of valuable information that is obtained from each event.
In normal PET scanners the photons that have lost more than a predefined maximum of energy due to being scattered (before reaching the detector) are rejected. This is done because taking these scattered events into account does not improve the image, it even degrades the image because the false information (noise) that is added is not outweighed by the valuable information that is acquired from these events.

In TOF-PET this energy selection of photons is also done, but since more valuable information is acquired per event, the predefined maximum of energy that photons may have lost can be increased. As a consequence of this, more events which would be rejected without the TOF information are now be accepted. This makes it possible to collect more data with a given dose to the patient (which is proportional to the total number of annihilation events over the lifetime of the radioactive isotope). This way the image quality can be improved by the noise reduction and/or the image acquisition time and dose to the patient can be reduced.

Determining scintillation pulse shapes

For TOF-PET to be applied successfully, sub-nanosecond timing resolution must be achieved at both detectors in coincidence. For this reason, the scintillation crystals and detectors used in PET must have excellent timing performance. Favorable scintillation crystal properties to achieve good timing resolution are a high light yield, a short decay time and also a short rise time, which all helps to achieve an accurate trigger on a scintillation pulse. By determining the scintillation pulse shapes of these crystals the rise time and decay time of the scintillation pulse can be obtained. Knowing the values of these parameters is important in making choices in the design of TOF-PET scanners, with respect to e.g. scintillator crystal material and the detector trigger schemes. This would be another step on the road to improve the timing resolution of determining photon timestamps, and thereby also of determining the difference in the timestamps of two coincident photons, leading to improved resolution and/or sensitivity of TOF-PET systems.

Also for the modelling of the physical processes involved in scintillations the knowledge of the rise time of the scintillation pulse is of great importance, since it is needed as an input parameter in simulation models.

Some crystals used in PET, such as LSO (lutetium oxyorthosilicate) and the similar LYSO (lutetium-yttrium oxyorthosilicate) have very short scintillation pulse rise times of hundreds of picoseconds or even less. Because of these short times and limits on the timing resolution of measurement systems, there is currently only little information on the rise times of the scintillation pulses of some fast scintillation crystals, when excited by 511 keV photons. This makes the rise times of these fast PET scintillation crystals an appealing object of research.

Scope of the present research

The present work aims to develop a measurement procedure suitable for determining scintillation pulse shapes of PET scintillation crystals with sub-nanosecond timing resolution, with the emphasis on characterizing the rising edge of the scintillation pulse. In addition, the procedure should be relatively easy to implement, allowing for routine measurements on new crystals and for good reproducibility. Different variations of setups that are considered to be viable ways to achieve this goal are investigated, addressing the technical implementations and showing some results of these setups. The results are compared and discussed, providing a proof-of-principle of the applicability of a suitable measurement procedure.
Chapter 1

Methods and materials

1.1 Time-correlated single photon counting

When measuring a scintillation pulse shape, using a setup which directly samples the
scintillation pulse yields less than optimal temporal resolution. This is caused by the
fact that the pulse is always convolved with the transfer function of the electronics
used. On the time-scale of PET scintillator pulse rise times this effect is degrading
the timing resolution too much to be able to accurately determine the scintillation
pulse shape, especially the rising edge. Therefore, instead of sampling the pulse
directly, the shape of the pulse is deduced from a large collection of samples of the
same kind of scintillation pulse by using the time-correlated single photon counting
(TCSPC) principle, described by Bollinger and Thomas.[15]

1.1.1 Basic principle of determining light pulse shapes using
TCSPC

Using the TCSPC method, the time dependence of the intensity of a light pulse
(the pulse shape, \(I(t)\)) can be determined. To make this possible a large number
of light pulses with the same pulse shape, e.g. scintillation pulses from the same
crystal, must be studied. For each of these light pulses the time that it originates
must be determined accurately. At this time a logic pulse is produced (the start
pulse), which is used as the ‘start’ input of a time-to-amplitude converter (TAC),
or some other time interval measuring device. The time that the TAC receives the
start pulse is referred to as \(t_{\text{start}}\). The TAC also needs a ‘stop’ input and the time
that it receives a stop pulse is referred to as \(t_{\text{stop}}\). The stop pulse is defined by the
time that a light detector looking at the light pulse detects the first photon from
this light pulse. The output of the TAC is a measure of the length of the time
interval in between the start pulse and the stop pulse: \(t_{\text{stop}} - t_{\text{start}}\). The stop pulse can be in principle occur at any time within the duration of the pulse, but if a lot
of light from the light pulse is allowed to hit the detector, then the probability is
high that the stop pulse occurs shortly after the start pulse, leading to measuring
almost exclusively short time intervals. This must be prevented and therefore the
light is attenuated so much that the expected (average) number of photons that
reach the detector (within a predefined maximum time interval) per light pulse is
small (\(< 1\)). This number is called the ‘stop to start ratio’ and is denoted by \(\epsilon\).

When a large number of time intervals is collected this way, a histogram can
be constructed of all of these intervals. With increasing number of measured light
pulses (events), this histogram converges to the probability density function \(P(t)\)
that describes the probability to measure the first photon at the time \(t\) after the start
pulse, given that a photon will be detected at some time in the coincidence window.
This coincidence window, or sampling period, is defined as the preset time interval
that the TAC is accepting a stop pulse after a start pulse was received. Finally, the
value of the probability density function (pdf) at the time \(t\), is proportional to the
intensity of the light pulse at the time \(t\), so \(P(t) \sim I(t)\). Therefore, by finding the
shape of \(P(t)\), the pulse shape of the light pulse, \(I(t)\), is found.
1.1.2 Bias in TCSPC setups

One limiting factor for this kind of setups is that the stop to start ratio, $\epsilon$, must not be too large. Since the stop detector triggers at the moment that the first photon arrives, any following photons arriving later within the sampling period are not collected, because of the detector’s inherent dead-time. This means that in all cases that in fact more than one photons arrive within the sampling period (these cases are called biased events), the pdf $P(t)$ has higher amplitude at shorter times. This is caused by the fact that for larger times the probability that there was no photon before the time $t$ decreases more rapidly if there are multiple photons arriving within the sampling period. The result of taking these biased events into account is a change of shape of the histogram, so that it no longer exactly represents the light pulse shape. The fraction of events that are biased in this way can be found by using Poisson statistics to be $\epsilon/2$, as described by Moses.[16] If this fraction is negligible, $P(t)$ is proportional to the intensity profile, so that the histogram will converge to this profile as well. If the fraction is larger, a correct model is needed to fit the histogram, which should take into account the change of shape caused by the biased events.

As a rough check if the value of $\epsilon$ (and thereby the bias) is not too large when measuring scintillation pulses, the decay time of the scintillation pulse can be compared to a reference value (e.g. a value determined in a setup with a known small bias). Checking the decay time is most effective because the effect of the bias is becoming increasingly strong for longer times, thus affecting the decay time much more than the rise time of the pulse.

1.1.3 Acquiring a start pulse

The method of acquiring a start pulse does in principle not influence the pulse shape that is determined. The only requirement is that it should mark the start of the light pulse accurately. There is a number of ways to acquire such a start pulse. One of these ways can be applied in most TCSPC setups where the light pulse is triggered externally, for instance when a scintillation crystal is excited by a short laser pulse or X-ray pulse. If the scintillation pulse is triggered by such an externally controlled excitation it is usually possible to get a logic pulse from the source of excitation (e.g. the laser) which marks the time that the excitation pulse is produced. This logic pulse can be used as the start pulse.

In this work, the above method of acquiring a start pulse cannot be applied. This is because in the present work scintillation pulses are studied which are not excited by an externally controlled excitation pulse. Instead, the scintillations are triggered by photons emitted from a radioactive source, since this is also what happens in PET scanners. Because this is a random process it is not known a priori when a radioactive decay event occurs and, consequently, when a scintillation occurs. Therefore, in the various setups presented in this work, two different methods of acquiring a start pulse are applied, which are both variations of the same principle. Both variations require the use of a second light detector, which will be referred to as the start detector, in addition to the detector that is used to acquire the stop pulse, which will be referred to as the stop detector.

In the first variation both detectors are looking at the same scintillation pulse. The scintillation crystal is optically coupled to the start detector in order to optimize the light collection at the start detector. From this start detector’s signal a trigger is extracted, using electronics, and this trigger is used as the start pulse. If the light collection at the start detector is optimized and the start detector achieves high timing resolution, the uncertainty in this start pulse is small. Some of the scintillation light is not collected by the start detector and leaks out of the crystal towards the stop detector, which then produces the stop pulse.

The second variation can only be applied for scintillation pulses which are excited by annihilation photons. The advantage of using annihilation photons is that they are always produced in pairs, both photons being emitted simultaneously. This fact makes it possible to use an additional scintillation crystal, so that for both the start detector as well as the stop detector a separate crystal is used, and both detectors are no longer looking at the same scintillation, but at the scintillations in their own
crystal instead. Since the scintillations in both crystals are coincident (occurring simultaneously), the start pulse can be acquired by triggering on the start detector’s signal in the same way as described in the first variation.

1.2 Setup components

In the present work the TCSPC method is applied to study scintillation pulses in LYSO crystals (Crystal Photonics, Inc) with the dimensions of 3x3x5 mm$^3$. The crystals were irradiated by 511 keV annihilation photons. These annihilation photons were produced in a $^{22}$Na source, which is a $\beta^+$ emitter, with an activity of approximately 1 MBq.

Various TCSPC setups were developed. The early setups make use of a TAC, like in the original method described in section 1.1.1. In these setups analog electronics are used. After making great effort in an attempt to improve the timing resolution of the analog setup without achieving the required resolution, it was concluded that this setup was not simple to implement and therefore does not satisfy the requirements as described in the scope of this research. Therefore it was decided to move towards a setup digitizing complete time traces of the detector signals. Descriptions of the analog setups are included in appendix A.

In the final setup an SiPM was used as the start detector, as described in section 1.2.1. An ID Quantique ID100 single photon detector was used as the stop sensor, which is described in section 1.2.2. In this setup the TAC, which records the time triggers, was taken out and a 10-bit digitizer was used to sample time traces of the detector signals and provide digital instead of analog time-pickoff, as described in section 1.3.

1.2.1 Start detector, SiPM

The SiPM device (Hamamatsu MPPC-S10362-33-050C) consists of an array of 3600 Geiger-mode APDs on an active area of $3 \times 3$ mm$^2$, each with its own quench resistor (together called a microcell), connected in parallel on a silicon substrate with a 50 $\mu$m pitch. The LYSO crystal was optically coupled to the SiPM using a silicone encapsulation gel (Lightspan LS-3252) and enclosed in a reflective casing. This casing was made of Spectralon®, a PTFE based material with a reflectivity specified to be better than 98% at 420 nm (the main emission wavelength of LYSO). The bias voltage to the SiPM is set to a little more than 70 V. Two generations of preamplifiers were used, both made in-house.[17] In the single crystal setups, which are described in section 1.4, a preamplifier was used with a cascaded amplification in two stages: the energy signal is the output of the first amplification stage (12x) and the timing signal is subsequently amplified for another factor of 5. The dual crystal setups, which are described in section 1.5, use a new generation of preamplifiers, which have two separate branches: one for the energy and one for the timing signal.

In the SiPM one single electron-hole pair can initiate an avalanche in a microcell. This electron-hole pair in an SiPM can be generated either by an incident photon or internally by thermal generation effects, after-pulses or optical cross-talk, all of which are responsible for dark counts.[18] However, in all of the setups using the SiPMs in this work an energy threshold is used to reject these dark counts, since they deposit too little energy in the detector. This energy threshold is applied to the summed signal of all cells, which is the only measure of the energy that is available, since each cell operates in Geiger-mode and therefore does not provide any energy information on its own.

Even though the energy threshold serves to reject single-cell dark counts, random counts can still be produced by scintillation events triggered inside the crystal randomly, caused by the intrinsic radioactivity in the LYSO originating from the lutetium. Some of these scintillations have sufficient energy to exceed the energy threshold, thus producing random counts. The count rate of the SiPM due to this intrinsic activity was determined, by putting the detector in a dark environment without a source in place, to be approximately 7 counts per second.
1.2.2 Stop detector, Geiger-mode APD

The stop detector is an ID Quantique ID100 device, which is a single cell Geiger-mode APD (GM-APD) with an active surface of 20x20 $\mu$m$^2$. The timing resolution was determined to be 70 ps in terms of full width at half maximum (FWHM).[19] The small active surface combined with active cooling results in a very low dark-count rate of 0.1 counts per second on average in a dark environment.

1.2.3 Electronic modules

The discriminators used in the dual crystal setup were the modules of a Philips Scientific (PS) model 710 octal discriminator. The timer unit used was a PS model 794 quad gate/delay generator. The logic unit used was a PS model 754 quad four-fold logic unit. The energy signal was amplified by a CAEN model N5688 16-channel spectroscopy amplifier and digitized using a CAEN model V785 32-channel peak-sensing ADC. The time traces were digitized by an Agilent Acqiris DC282 10-bit-digitizer.

1.3 Digital time-pickoff

Digital time pick-off can be used as an alternative for using analog electronics to create a start pulse and a stop pulse. Instead of using these analog pulses, a timestamp is determined digitally from the sampled time trace of the start detector’s signal (the start trace) and the corresponding trace from the stop detector’s signal (the stop trace). Typical sampled start and stop traces are depicted in figures 1.1 and 1.2 respectively.

The digital time pick-off is done in three steps. First: the datapoint that is closest to a coarse-set threshold level is found (since the traces consist of equally spaced in time datapoints 125 ps apart, the accuracy of this first threshold crossing timestamp is no better than 125 ps). This coarse threshold level must be set such that it is above the noise level of the sampled traces of most of the events and such that most traces cross this threshold in the rising edge of the pulse.

Secondly a part of the trace of length 5 ns, centered around the datapoint that was found (see above), is interpolated to more closely spaced in time points of 1 ps apart. The type of the interpolation is a cubic spline from the curve fitting toolbox in MATLAB. After the interpolation is done, the interpolated curve is corrected for any possible baseline offsets. This is done by determining the baseline of the interpolated curve by averaging a part of the curve preceding the coarse threshold crossing and subtracting this baseline value from the interpolated curve.

Thirdly, the interpolation is used to find the timestamp of the trace. This timestamp is defined by the crossing of the baseline corrected interpolated curve with a fine-set threshold. This threshold level is set such that the resulting timing resolution of the determined start trace timestamps is optimized. The determination and optimization of the timing resolution for the start timestamps was done in a separate experiment, which is described in section 1.8.1.
Figure 1.1: A typical start trace, showing the threshold crossing. The inset shows a magnification of the part where the threshold is crossed. Digitized datapoints (125 ps sampling interval) are shown in blue, datapoints that were interpolated are marked with a red ‘x’. The interpolation is shown as the magenta solid line and the threshold crossing is marked by the cross hairs.

Figure 1.2: A typical stop trace, corresponding to the start trace in figure 1.1, showing the threshold crossing. The inset shows a magnification of the part where the threshold is crossed. Digitized datapoints (125 ps sampling interval) are shown in blue, datapoints that were interpolated are marked with a red ‘x’. The interpolation is shown as the magenta solid line and the threshold crossing is marked by the cross hairs.
1.4 Single crystal setup

1.4.1 Configuration of the main components

In the first setups using the SiPM and the ID100 detectors, one single LYSO crystal is used, which is polished at all sides and optically coupled to the SiPM start detector. The SiPM and the ID100 detector are facing each other (as shown in the schematic in figure 1.3). The crystal is encapsulated in reflective material at all sides, except for the side that faces the ID100 stop detector and the side that was optically coupled to the SiPM’s active surface. Scintillation light is allowed to leak out of the crystal towards the stop detector.

Two variations of the setup are used. In the first variation there is no pinhole in between the crystal and the stop detector. In the second variation the pinhole, shown in figure 1.3, is included.

Both detectors are placed on an optical rail, making it possible to align the components and tune count rates at the stop detector. The setup is placed in a dark box to prevent the detection of ambient light. All experiments are conducted at room temperature.

1.4.2 Setup essentials

A schematic of the electronics used in the experiment is also shown in figure 1.3. The timing signal from the SiPM is sampled by the Acqiris DC282 for digital time pickoff (see section 1.3) and the energy signal is used for online (during measurement) preselection of events (as described in section 1.4.3). In order to allow offline energy selection at the data analysis stage, as described in section 1.6.1, the energy information is digitized by a CAEN V785 peak-sensing ADC.

The ID100 produces a (logic) pulse at the time that the first photon is detected. This signal is also sampled by the Acqiris DC282 to allow digital time pickoff.

The full-scale of both sampling channels of the Acqiris DC282 is set to a small part of the amplitude of the signal (for the SiPM’s signal the full-scale is just enough
to determine a timestamp at a threshold above the noise level). This way as little as possible digitization noise is added.

Digitizing both the start and stop traces assures optimal temporal resolution in the determination of the time difference between the start and stop signals. However, it does assume that there are two high sample rate digitizers available to sample both time traces. Yet even without two of these digitizers, there is another way to determine the time difference. This is by relating the start timestamp to the stop trigger, as described in section 1.5.2.

1.4.3 Online event selection and trigger logics

Much of the circuitry involved serves to select events online. This selection is necessary to reduce the number of recorded unuseful events, e.g. non-coincident or scattered photon detections, which produce a large amount of data per sampled event and even, in a worst-case scenario, could cause loss of synchronization between the energy and time samples. The actual selection is done in the logic units, shown in figure 1.3, which both perform the logic AND operation.

The upper logic unit serves to select the scintillation pulses with an energy above a predefined threshold level and its output represents a leading edge trigger from these scintillation signals. This is realized as follows. The SiPM’s energy signal is split by a 50 Ω splitter. One of the twin signals is delayed by several tens of nanoseconds, the other is not. The non-delayed ('energy') signal is the input of a leading edge discriminator, which is used to set an energy threshold. This threshold is set to just below the full photon absorption peak at 511 keV (such that all Compton scattered photons are rejected). The delayed ('timing') signal is passed through a second discriminator, which is used to obtain an accurate leading edge trigger from the signal. Its threshold is set to a low level, ensuring little time-jitter by triggering in an early stage of the rising edge of the pulse. Both the signal from the energy discriminator as the signal from the timing discriminator are provided as inputs for the upper logic unit, which performs the AND operation on both inputs. Because of the delay in the timing signal, the energy signal always comes in first, so the AND unit is armed if a scintillation occurs with sufficient energy to exceed the energy threshold. Shortly after that, the input from the timing discriminator arrives and the AND unit is fired. This way, the output from the AND unit represents an accurate leading edge trigger from the SiPM’s energy signal for scintillation events which are selected to exceed the predefined energy threshold.

The lower logic unit is the one that triggers the sampling of the time traces. This trigger is produced in the case that three conditions have been met:

1. There must be an event at the start detector with an energy above the predefined threshold level.
2. There must be an event at the ID100 within the coincidence window. This window is set by stretching in time the signal that indicates that condition 1 is true. The coincidence window was set to about half a microsecond, which corresponds to 10-15 decay times of an LYSO scintillation crystal, which is approximately 40 ns.[20]
3. The peak-sensing ADC must not be 'busy'. This condition is incorporated to avoid cases in which a time trace would be sampled while the peak-sensing ADC does not collect the associated energy information. This scenario would result in loss of synchronization between energy and time information.

If these three conditions are met, the Acqiris DC282 is triggered to sample both time traces and it in turn triggers the peak sensing ADC to sample the energy of the SiPM pulse signal. The sampling of such an event will be referred to as a valid coincidence event.
Figure 1.4: Electronics of the setups using two crystals. The dotted components may be omitted in a setup digitizing only the SiPM’s trace.

1.5 Dual crystal setup

1.5.1 Setup digitizing both the start and stop signals

Another variation of the setup was developed by making some modifications on the single crystal setup. The most important modification is the introduction of a second crystal, which is optically coupled to the ID100 stop detector. Both crystals were etched on five sides (all sides except for the side with the optical coupling), instead of being polished, as in the single crystal setup. Furthermore, a light block in between the two crystals was introduced, which replaces the pinhole in figure 1.3 and serves to prevent light to reflect from the source holder back into the stop crystal and detector. A schematic of the electronics used in this setup is shown in figure 1.4 (Shown in a dotted style are the components that are omitted in the setup described later in section 1.5.2.) Other minor modifications of the setup include using a different dark box, which is assumed to be comparably light-tight as the old box, but provides better electronic shielding. Also the trigger logics are implemented in a slightly different way. Since the basic principles of the setup and the logics remain the same, the details of the trigger logics in this setup are explained in appendix C.

The modification of adding a crystal increases the valid coincidence events count rate significantly because the detection of a stop is no longer dependent on the very small amount of light that is allowed to pass through the pinhole. Instead the stop crystal is now optically coupled to the stop detector. The modification also improves the SiPM’s temporal resolution because the crystal is now wrapped in Spectralon® at all sides, except for the side that is coupled to the detector. That implies there is more efficient light collection than in case that the crystal has one free side towards the stop detector, improving the timing resolution.

1.5.2 Setup digitizing the start signal only

Realizing that the stop detector’s output is a logic pulse, a smaller setup was developed, which enables leaving out the dotted components in figure 1.4 by using only the digitized time traces of the SiPM’s signal. Digitizing only the start traces saves one of the two state-of-the-art digitizers, which of course saves both money and experimental resources. This setup was tested by using the dual crystal setup and discarding all stop traces in the data analysis.
The basic principle behind the single trace setup is to take the start timestamp relative to the trigger which starts the digitization of the trace, instead of taking it relative to the stop timestamp (as shown in figure 1.5). The reason that this procedure should in principle yield the same scintillation pulse shape is that the trigger that starts the digitization of the time trace represents a delayed version of the ID100’s stop pulse. At the moment that the sampling trigger (i.e. the delayed stop pulse) comes in, the start pulse naturally lies in the past, but the digitizer has a data buffer, which can be made long enough to still contain the start pulse at the time that the trigger comes in. The buffer is then read out and the zero of time is assigned to the first datapoint after the trigger comes in.

To be able to accurately compare the start timestamp to the moment that the stop pulse occurs, the trigger jitter must be as small as possible. This trigger jitter is caused partly by the fact that the trigger comes at a random time in between two datapoints. This means that there is a random time interval between the ‘zero-of-time datapoint’ and the actual trigger and the length of this interval ranges between zero and the sampling interval of 125 ps. This time interval will be referred to as the trigger delay (as indicated in figure 1.5). Now the correct time interval between the start timestamp and the stop trigger is found by determining the start timestamp with respect to the zero-of-time datapoint in the digitized trace and then correcting for the trigger delay. This trigger delay is estimated by the digitizer and stored for each digitized trace and is read out and used as a correction in the data analysis stage. The trigger jitter, corrected using the trigger delay estimate can be as small as 66 ps FWHM. (In appendix B the determination of this number is described.)

1.6 Offline event selection

In between finding the datapoint that is closest to the coarse-set threshold level (step one of the digital time pickoff, section 1.3) and interpolating the traces (step two), a few selection procedures are carried out. These are described in the following two sections.

1.6.1 Refining the energy selection

To achieve a good timing resolution, events with an energy less than the full photon absorption energy (511 keV), such as Compton scattered photons, must be rejected. These lower energy events degrade the timing resolution because they yield less light in the scintillator and thus reduce the slope of the rising edge of the scintillation signal, increasing time-jitter on the start pulse. The rejection of low energy events was already done partly during the measurement, using electronics to reject roughly all photons with an energy lower than the full absorption peak. This can be refined digitally and also the events with energy above the 511 keV photo-peak can be rejected. Applying this fine selection, including the rejection of higher energy events, helps to reduce the amplitude walk of the leading edge trigger. To do this, a
MATLAB routine was used to create a histogram of the SiPM’s energy signal of all events to create an energy spectrum and fit a gaussian at the 511 keV full energy absorption peak and take the full width at tenth maximum (FWTM) of this gaussian as the energy window in which events are selected.

1.6.2 Rejecting trigger-on-start events

If a random pulse occurs at the stop detector more than 140 ns before a start pulse occurs, both of these pulses will overlap at the input of the logic AND unit which does the coincidence selection (described in the trigger logics section 1.4.3). But since in this case the pulse from the stop side arrives before the pulse from the start side, the AND unit is armed by the stop pulse and fired by the start pulse. As a consequence of this, the sampling of the time traces is not triggered by the stop pulse, but by the start pulse instead. In that case there is no way of knowing the time that the stop pulse occurred when using the setup digitizing only the start signal, and the ‘single trace analysis’ from section 1.5.2 fails. Therefore, these events must be rejected.

To implement the selection, the following observation is used: in normal events the stop trace is the source of the sampling trigger, so the sampled stop trace is always positioned at the same place on the (sampling) time axis. In case the sampling was triggered by the start trace, the stop trace is nearly always found at a very different place on the time axis. So when the stop trace is found at a place on the time axis different from the normal place, the event is rejected.

In practice, this selection corresponds to rejecting all cases that a dark pulse occurs at the stop detector at more than 140 ns before the start pulse and the selection was only applied in the dual crystal dual trace setup (for both the single trace and the dual trace analysis).

1.7 Data analysis

The histogram of the arrival times (timestamps) of the first photon after the start of a scintillation pulse is assumed to converge to the pulse-shape of the scintillation pulse, as described in section 1.1.1. A fairly simple model can be assumed to describe this pulse-shape analytically. The model assumed here consists of a rising exponential, $E_r(t)$, with rise time $\tau_r$ to describe the rising edge of the pulse and a decaying exponential, $E_d(t)$, with a decay time $\tau_d$ to describe the falling edge of the pulse. However, since the detectors have a finite temporal resolution, the pulse shape that the histogram converges to, is blurred. To take this into account, the described pulse-shape of the two exponential factors is convolved with a gaussian, $G(t)$. Defining the components of the fit as follows:

$$E_r(t) = 1 - \exp\left(-\frac{t - t_0}{\tau_r}\right), \quad E_d(t) = \exp\left(-\frac{t - t_0}{\tau_d}\right), \quad G(t) = \exp\left(-\frac{t^2}{2\sigma^2}\right)$$

The parameters in these expressions are the standard deviation of the gaussian: $\sigma$, the rise- and decay times: $\tau_r$ and $\tau_d$, and the start time: $t_0$.

The rising exponential, $E_r$, is defined zero for $t < t_0$, which can be seen as multiplying it with a unit step function, $s(t - t_0)$. Now the fit function is defined as the convolution of all these components:

$$f(t) = B + A \cdot C \cdot \int_{-\infty}^{\infty} G(t - \tau) \cdot E_r(\tau) \cdot E_d(\tau) \cdot s(\tau - t_0) d\tau$$

$$= B + A \cdot C \cdot \int_{t_0}^{t_{\text{end}}} G(t - \tau) \cdot E_r(\tau) \cdot E_d(\tau) d\tau$$

The factor $C$ is a normalization constant, which is equal to $(\tau_r + \tau_d)/(\sqrt{2\pi}\sigma\tau_d^2)$ and $A$ is the area under the function. $t_{\text{end}}$ is the end of the time-axis of the histogram that is fitted, which is set manually to a little before the end of the coincidence.
$B$ is a constant offset to incorporate a first order correction for random coincidences ('background counts').

The method used to find the best fit is minimizing the sum of the squared errors, defined as the sum of the squared deviations of all points in the histogram (where a point is the bin count of the bin centered at the time $t$) from the fit-function at the same time $t$. The sum of the squared errors is defined as a function of the parameters $\tau_r$, $\tau_d$, $A$ and $t_0$. This function is supplied as the input of the MATLAB function 'fminsearch', which tries to minimize it by varying the parameters.

The offset constant $B$ is not part of the fit and is determined by averaging the bin count of the bins at all times before the onset of the pulse. The parameter $\sigma$ is not part of the fit either and is set manually to correspond to the system resolution (specified in FWHM). The relation between $\sigma$ and the FWHM of the gaussian is given by

$$\sigma = \frac{\text{FWHM}}{2 \cdot \sqrt{2 \cdot \ln 2}} \approx \frac{\text{FWHM}}{2.355}.$$  

1.8 System resolution

In all setups, even if false coincidences and all other sources of errors related to the process itself would be absent, there is still the uncertainty introduced by the measurement and analysis devices. In the following sections the uncertainties associated with the various devices are addressed.

1.8.1 Resolution of the start and stop detector

The determination of the timing resolution of the SiPM detectors was done in a separate experiment, outside of this work.[17] In this experiment two identical SiPM detectors were used, detecting scintillation pulses excited by coincident 511 keV annihilation photons. Both detectors were fitted with an LYSO crystal, optically coupled to the detector’s active surface.

Using this separate setup, the coincidence resolving time (CRT) of the system of two of these identical SiPMs was determined as a function of threshold level. The optimal threshold level was found by choosing the level that yields the smallest CRT. By the assumption that both detectors are identical, the timing resolution of one single SiPM detector is found by dividing this number by $\sqrt{2}$. Since the detectors used in the single crystal and dual crystal setups are different in some aspects, the timing resolution is determined separately for both types.

With the SiPM used in the single crystal setup (section 1.4), some light is allowed to leak out of the crystal and the early type of preamplifiers was used. The CRT of this system of two of these detectors when detecting coincident scintillations was determined to be 228 ps FWHM, corresponding to a timing resolution of $228/\sqrt{2} = 161$ ps FWHM for the SiPM in the single crystal setup.

The SiPM used in the dual crystal setup (section 1.5) has improved timing resolution, mainly due to the improved light collection and also by the use of the new type of preamplifiers. The timing resolution of one such an SiPM, which was used in the dual crystal setup, was determined to be 97 ps FWHM.

Finally, there is also the timing resolution of the ID100 stop detector, which was determined to be 70 ps FWHM[19], so that the timing resolution of system of the start and stop detector, which is determined by summing both contributions quadratically, amounts to $\sqrt{161^2 + 70^2} = 176$ ps FWHM for the single crystal setup and similarly 120 ps FWHM for the dual crystal setup.

1.8.2 Trigger jitter

For the analysis by taking the start timestamps relative to the trigger ('single trace analysis', section 1.5.2), there is the additional trigger jitter, which is unknown in a setup where only the start signal is digitized. However, in setups that digitize both the start and the stop signals while, for testing purposes, the single trace analysis is
used, the trigger jitter can be determined from the timestamps of the stop traces. This is done with the dual crystal setup presented in section 1.5.

1.8.3 Synchronization

When digitizing both traces, the synchronization error between the digitizing cards has to be considered as a possible source of timing jitter, but since both digitizing cards use the same internal clock which has a timebase accuracy specified to be better than 2 ppm, this synchronization error is negligible.

1.8.4 Interpolation and timestamping

The additional timing jitter introduced by the determination of the timestamps from the digitized time traces (using an interpolation, as described in section 1.3) is assumed to be negligible. This assumption is supported by the fact the stop pulse is a logic pulse, so that the sampled traces have a steep rising edge and therefore small jitter on the determination of the timestamp. For the start detector this is not an additional error, because it is already included in the detector resolution that was determined from the CRT measurements\[17\], as described in section 1.8.1.
Chapter 2

Results

2.1 Single crystal setup

2.1.1 No-pinhole setup

The scintillation pulse shape determined from the data from the single crystal setup, without the pinhole in between the crystal and the stop detector, is shown in figure 2.1. This figure shows the histogram of the differences between the start and stop timestamps. The histogram bin width, which is given in the caption of all figures, is chosen such that the data is presented clearly in the figure. In the fitting procedure a smaller bin width was used, 5 ps in all of the figures, since at these small bin widths the values of the fitted parameters do not depend significantly on the bin width, as is shown in section 2.2.3. The fitted functions shown are scaled by the ratio of histogram bin width to fit bin width, to allow comparing the fit to the data.

![Histogram of the time-differences between start- and stop timestamps](image.png)

Figure 2.1: Histogram of the time-differences between start- and stop timestamps (112,000 energy selected events in total), on a logarithmic y-scale, using a bin width of 100 ps. This data was acquired using the single crystal setup, without the pinhole. Also shown is the fitted function and the rise- and decay times of the fitted function. The inset shows, on a linear scale, a zoom on the rising edge of the pulse. The high (black) and low (green) curves indicate the effect of changing the rise time manually to 0.4 ns and 0.8 ns respectively, while keeping all other parameters constant. The system resolution constant in the fit was set to 176 ps FWHM.
The rise time of the pulse is determined to be 0.6 ns with an estimated uncertainty interval of [0.4, 0.8] ns. This estimated uncertainty interval is determined by manually varying the rise time parameter in the fit function, keeping the other parameters constant, to visually show the upper and lower boundary value of the range of times where the true rise time most probably lies within. The data acquisition rate for this setup is 25-30 valid coincidence events per minute. This implies a measuring time of about half a week up to one week to acquire 200,000 events, which is the number that was striven for. The system resolution parameter of the fit was set to the quadratic sum of the timing resolution of the start detector (161 ps) and the stop detector (70 ps), which amounts to 176 ps FWHM for this single crystal setup.

2.1.2 Pinhole setup

The single crystal setup that included a pinhole in between the crystal and the stop detector produced a limited amount of results: the histogram contains only 22,000 energy selected events (counts) in total, at most about 60 entries per 100 ps bin, as shown in figure 2.2. The rise time of the pulse was determined to be 0.3 ns with an estimated uncertainty interval of [0.2, 0.4] ns.

The low number of counts is a consequence of the slow data acquisition rate involved with this setup. The acquisition the 40,000 events (before energy selection) took two weeks, corresponding to a very low count rate of 2 counts per minute. Therefore the experiment was terminated before the number of 200,000 events was reached.

![Figure 2.2: Histogram of the time-differences between start- and stop timestamps (22,000 events in total), on a logarithmic y-scale, using a bin width of 100 ps. This data was acquired using the single crystal setup, including the pinhole. Also shown is the fitted function. The inset shows, on a linear scale, a zoom on the rising edge of the pulse. The high (black) and low (green) curves indicate the effect of changing the rise time manually to 0.2 ns and 0.4 ns respectively (keeping all other parameters constant). The system resolution constant in the fit was set to 176 ps FWHM.](image-url)
2.2 Dual crystal setup, digitizing both traces

The dual crystal setup that was equipped with two Agilent Acqiris DC282 10-bit-digitizers digitized both the start and the stop traces and can be analyzed using two different methods. The results of using these different approaches are shown in the following two sections. First the data is analyzed using the differences between the timestamps from both traces (section 2.2.1) and subsequently the data is analyzed using only the timestamps of the start detector (corrected for trigger delay, section 2.2.2).

2.2.1 Two traces analysis

The histogram of the timedifferences between start- and stop timestamps, acquired using the dual crystal setup is shown in figure 2.3. The dual crystal setup yields an increase in the valid coincidence events count rate with respect to the pinhole setup, to almost 20 counts per minute. 300,000 events were collected in this measurement (268,000 were left after the selection procedures). When using the two-traces analysis the system resolution consists only of the contributions due to the start and the stop detector (97 ps and 70 ps respectively), which amounts to a total resolution of 120 ps FWHM. Using this setup, the rise time was determined to be 81 ps, with an estimated uncertainty interval of [50,120] ps.

2.2.2 Single trace analysis

The histogram of the timestamps of the start detector, acquired using the dual crystal setup is shown in figure 2.4. When using the single trace analysis the system resolution is slightly worse than in the case that the two-traces analysis is used, because now the trigger jitter has to be taken into account. The trigger jitter was determined in terms of the spread in the stop timestamps to be 113 ps FWHM, as described in section 2.2.4. The corresponding system resolution constant (including the resolutions from both detectors) for the fit in figure 2.4 was set to 165 ps. Using this setup, the rise time was determined to be 77 ps with an estimated uncertainty interval of [40,110] ps.
Figure 2.3: Histogram of the time-differences between start- and stop timestamps (268,000 energy selected events in total), on a logarithmic y-scale, using a bin width of 50 ps. This data was acquired using the dual crystal setup. Also shown is the fitted function. The inset shows, on a linear scale, a zoom on the rising edge of the pulse. The high (black) and low (green) curves curves indicate the effect of changing the rise time manually to 50 ps and 120 ps respectively (keeping all other parameters constant). The system resolution constant in the fit was set to 120 ps FWHM.

Figure 2.4: Histogram of the start timestamps from the same events (acquired using the dual crystal setup, digitizing both traces) as in figure 2.3, on a logarithmic y-scale, using a bin width of 50 ps. Also shown is the fitted function. The high (black) and low (green) curves curves indicate the effect of changing the rise time manually to 40 ps and 110 ps respectively (keeping all other parameters constant). The system resolution constant in the fit was set to 165 ps FWHM.
2.2.3 Bin width dependence

The effect of varying the bin width in the histogram that is fitted by the fitting procedure, as described in section 1.7, was investigated. Shown in figure 2.5 is the change in the fitted rise time as an effect of fitting the same data using histograms with different bin widths. The data in all of the histograms is the same for all values in the figure, it consists of the time differences between start and stop timestamps, acquired by the dual crystal setup, using a system resolution constant of 120 ps FWHM. It can be noted that the fitted value of the rise time is stable within plus or minus 1 ps at bin widths of 10 ps or less. At intermediate bin widths the behavior of the fit becomes slightly less predictable and at relatively large bin widths the fitted rise time is varying a lot when changing the bin width. For this reason all fits are carried out at a bin width of 5 ps, which is well in the region where the fitted rise time is stable with varying bin width.
Figure 2.6: Stop detector timestamps relative to the trigger, with a gaussian fit (all distributions shifted with same time to center the mean of part 2 at zero). 95% confidence intervals of the fit are, for the FWHM: 1.6 ps, 1.3 ps and 0.35 ps respectively; and for the mean: 0.7 ps, 0.5 ps and 0.15 ps respectively. The effect of the recalibration of the Acqiris DC282 before conducting part 3 of the measurements is clearly visible by the significant decrease in the width of the distribution.

2.2.4 Determining the trigger jitter for the single trace analysis

The trigger jitter in the dual crystal setup shows an apparent change over the course of the measurement, as shown in figure 2.6. This figure shows the stop timestamps from three separate parts of the measurement, 100,000 events each. In the first two parts the jitter is significantly larger than in the last part, where the optimum of 66 ps FWHM is achieved. The improvement is due to a recalibration of the Acqiris DC282 before starting the final part of the measurement. In order to obtain one effective value for the system resolution, the overall trigger jitter was estimated by fitting a single gaussian through the distribution of the stop timestamps from all three parts together. Although this distribution is not exactly gaussian, fitting a gaussian through this overall distribution is still done to obtain an estimate of an effective overall trigger jitter, because the fit routine also uses a gaussian to model the system resolution. The overall trigger jitter was determined this way to be 113 ps FWHM.
Chapter 3

Discussion and conclusions

3.1 Analog setups

The early experiments that were conducted using analog electronics and analog time pick-off were found to be inadequate for determining the scintillation pulse shapes of PET scintillators such as LYSO, especially the rising edge of the pulse, or the numerical value of the rise time. This was based on the observation that improvement of the system timing resolution to values below 300 ps was not achieved using this setup, which used a timing alignment probe (TAP) as the start detector and a PMT as the stop detector and analog time pick-off. Even after numerous attempts with different variations of this setup, further improvements were not achieved. From these results it was concluded that the analog setup is not the easy to implement procedure that was sought for. Therefore it was decided to move to a new setup, using an SiPM as a start and an GM-APD (ID100) as a stop detector and using digital time pick-off.

3.2 Single and dual crystal setups

3.2.1 Bin width dependence of fitted parameters

From the results of the setups using an SiPM and an ID100 (the single and dual crystal setups) histograms were constructed of the start and stop timestamps and these histograms were fitted to obtain the scintillation pulse shape. This fitting procedure has a significant uncertainty associated with it. To reduce this uncertainty, the fitting procedure was tuned by varying the bin width of the histogram. This is a trade-off between noise level per bin and the number of bins. The fitted rise times were found to be stable with respect to varying the bin width at very small bin sizes (smaller than 10 ps) and therefore in all fits a bin width of 5 ps was used.

3.2.2 Estimating the fit uncertainties

If the bin size is chosen this small, the histograms containing some 200,000 events are relatively noisy, and still the rising edge contains only a small part of all data points. Because of this the sensitivity of the fitted function to changes in the rising edge is limited. This causes the error bars on the fit parameters, especially the rise time, to be relatively large, although small in absolute value. In order to achieve even smaller uncertainties and to allow accurate error estimation, the noise must be reduced by increasing the number of events by a factor of 10 to 100. With the count rates that are realized currently, acquiring this number of events is impractical, because the measurement would take months. Therefore all the histograms shown are presented including a fit and a high and a low curve to show the influence of changing the rise time of the function manually (keeping all other parameters constant), to show a reasonable estimate of what the minimum and maximum values of the rise time could be to produce a realistic fit of the histogram data. Suggestions are made in chapter 4 on how to improve the setup to make it possible to acquire much more events in a reasonable amount of time.
3.3 Single crystal setup

Given the electronics used in the single crystal setups, the trigger jitter was too large to allow analyzing the data using only the start trace, so the focus is at the analysis using timestamps from both the start and the stop detector.

3.3.1 Sources of errors with all single crystal setups

As a consequence of not using a pinhole in between the crystal and the stop detector it is possible for photons to reflect multiple times between the non-active surface of the ID100, which consists of a reflective metal, and the Spectralon® wrapping of the SiPM detector, as illustrated in figure 3.1. These photons thus might cover several centimeters of distance before being detected. This effect introduces an additional spread in photon path lengths, corresponding to an additional time spread in the photon arrival times, causing eventually a blurring of the histogram.

The stop-to-start ratio, $\epsilon$, for the single crystal setup was determined to be about 0.3 percent. This leads to a fraction of biased events of half of this value (as described by Moses[16]), 0.15%, which will be neglected. The determination of $\epsilon$ can be done in a straight-forward way, because there is only one crystal, so that all stops can be associated with a well-defined start.

False coincidences might be another source of errors. A false coincidence occurs if the stop detector produces a pulse within the coincidence window which is not correlated with the start pulse. Such an uncorrelated stop pulse can be produced by a dark pulse in the stop detector. Since the dark count rate of the stop detector is low this source of error will be ignored for this setup.

3.3.2 No-pinhole setup

The results from the first of these setups, without the pinhole, show a fitted rise time of 0.6 ns, with an estimated uncertainty interval of $[0.4,0.8]$ ns. This value is significantly higher than the value found by Moses and Derenzo[21], who found 10%-90% rise times of 465 ps and 484 ps for two different polished LSO crystals of dimensions 3x3x3 mm, corresponding to exponential rise times of 212 ps and 220 ps respectively. Although these values cannot be compared with the present results directly because of the slightly different material (LSO instead of LYSO) and a different source of excitation (a light-excited X-ray source instead of annihilation photons), the scintillation pulse in the LYSO crystal was still expected to have a much shorter rise time than the 0.6 ns that was found. It was hypothesized that finding this higher value was caused by the additional photon arrival time spread due to a spread in photon path lengths. The histogram would then be blurred and the true rise time of the scintillation pulse would be smaller than the value determined with this setup.

3.3.3 Pinhole setup

The hypothesis that the determined value of the rise time of 0.6 ns is long due to the spread in photon arrival times is supported by the fact that the setup including the
pinhole in between the crystal and the stop detector yielded a significantly shorter rise time of 0.3 ns, with an estimated uncertainty interval of [0.2,0.4] ns (setting the same system resolution constant in the fit as with the data from the no-pinhole setup).

Since both the effect of false coincidences and a too high $\epsilon$ value, which could cause a bias towards early times in the pdf $P(t)$, are negligible, the determined decay time of this experiment is unbiased. The determined value of the decay time is 43 ns, both for the setup without the pinhole as for the setup including it. This value is close to reported values stating a decay time of 40 ns - 42 ns [20],[22]. This affirms the validity of the analysis performed on the data.

3.3.4 Conclusion

With respect to the rising edge, it was found that the single crystal setup results in either a pulse shape showing a rising edge which is predominantly determined by the photon arrival time spread (as with the no-pinhole setup), or in a large uncertainty of the determined rise time because of the large statistical noise caused by the very low count rate (as with the pinhole setup). The bias, however, in this setup is negligible, so that the determined decay time of 43 ns can be used as a reference for comparison with possibly biased setups.

An improvement of the single crystal setup was needed in order to determine the scintillation pulse shape, especially the rising edge, more accurately. The dual crystal setup was developed in an attempt to realize this.

3.4 Dual crystal setup

3.4.1 Sources of errors with all dual crystal setups

With the dual crystal setup, including the stop crystal, there is no one-on-one correlation between finding a scintillation in the start crystal and having one in the stop crystal. This causes a drawback of the dual crystal setup: the important value that should be restricted to be small is the expected number of photons that hits the stop detector given that a scintillation occurred in the stop crystal (this number would be the true stop-to-start ratio in this case and will still be referred to as $\epsilon$), but the value of $\epsilon$ cannot be determined directly in this case, since it is unknown how many scintillations in the stop crystal are occurring exactly. Checking if the decay time is correct is still an effective check whether the bias is small or not.

In the dual crystal setup, false coincidences can also occur with much higher probability. The stop detector now has its own crystal and it might detect a photon within the coincidence window which is not correlated with the photon that triggered the start detector (which actually opened the coincidence window). The intrinsic activity in the LYSO crystal from the lutetium adds to this false coincidence probability. This effect causes a bias towards early times in the histogram (it causes the probability to detect early photons to increase more than the probability to detect late photons). The effect of this bias in the data due to a possibly too large value of $\epsilon$ and/or a too high rate of false coincidences is almost exclusively visible at longer times, and very small in the rising edge (as described in section 1.1.2).

Although it is better to avoid biased results and the need to correct for this (by making some assumptions about the shape of the scintillation pulse), it is possible to correct for the bias with an elaborate fitting function, which includes extra parameters to describe the effects of the bias. However, since the effect of the bias is insignificant in the rising edge of the determined scintillation pulse, which is the most important part of the pulse to be characterized in the present research, this elaborate fitting procedure is beyond the scope of the present research. Here, the simple fit model is used as described in section 1.7.
3.4.2 Setup digitizing both traces, using two-traces analysis

The dual crystal setup achieves an improved system timing resolution as compared to the single crystal setup by using a fully encapsulated crystal instead of having one open surface and by using the new generation of SiPM preamplifiers. This improved system resolution makes the fit more sensitive to changes in the rise time parameter, yielding a smaller uncertainty. Also the photon path length spread is reduced significantly (the effect might still occur within the crystal, but since this is only $3\times 5\times 5$ mm$^3$ in volume, this effect is small). The rise time of 81 ps, with an estimated uncertainty interval of $[50,120]$ ps, is significantly shorter than what was determined by using the single crystal results. This again supports the hypothesis that the photon path length spread blurred the histogram of the single crystal data.

A bias in the results is apparent from the shorter decay time of 40 ns, as compared to the 43 ns of the single crystal setup, which is assumed to be unbiased. However, the effect of this bias on the rising edge of the pulse shape is insignificant, because the probability that a biased event occurs within the $\sim 100$ ps rise time (i.e. the probability that a second photon reaches the detector within the rise time of the pulse and will be missed by the detector) is very small. Therefore, the effect of the bias on the determined rise time is negligible.

3.4.3 Setup digitizing both traces, using single-trace analysis

With the current large uncertainty on the fitted rise times, the results from the single-trace analysis of the data acquired with the dual crystal setup are not significantly different from the results from the two-traces analysis of the same data: the single-trace analysis yields a rise time of 77 ps with an estimated uncertainty interval of $[40,110]$ ps. The system resolution that must be supplied as a fit function constant is larger than when using the two-traces analysis (because of the added trigger jitter contribution), but if this system resolution is accurately known, the fit can in principle correct for this. However, the fit does become less sensitive to varying the rise time parameter, which implies that the uncertainty in the fitted rise time could be reduced less (e.g. by collecting more data) than in case a better system timing resolution is achieved.

The following two observations with respect to the trigger jitter were made when using the single-trace analysis: first, analyzing the stop timestamps shows a drift of the trigger jitter over the course of time, and second, it is possible to get an optimized trigger jitter as small as 66 ps FWHM.

On the basis of these observations the use of a setup which digitizes only the start trace might be a viable alternative to digitizing both traces. This is, however, only true if the trigger jitter is optimized and determined accurately. The digitizer should be calibrated frequently to prevent large drifts in the trigger jitter. Drifts in the jitter would lead to a trigger jitter distribution which is not exactly gaussian, which would then be difficult to correct for in a simple fitting function.

If all this is done, and a trigger jitter of 66 ps FWHM would be assured, the system resolution would only increase from e.g. 120 to 137 ps FWHM, which might be considered to be an acceptable value.

3.4.4 Conclusion

Using the dual crystal setup yields a scintillation pulse shape with a significantly shorter rise time than using the single crystal setup. This is due to an effective reduction of the photon arrival time spread by using two crystals. The decay time determined from the dual crystal setup is 40 ns, which is shorter than what was found by using the unbiased single crystal setup, indicating a bias in the dual crystal setup. This bias, however, does not significantly influence the rising edge of the determined pulse shape. Therefore the rise time of the scintillation pulse determined by the dual crystal setup using the two-traces analysis: 81 ps with an estimated uncertainty interval of $[50,120]$ ps, is considered the most accurate determination of the exponential rise time of the scintillation pulses in LYSO, excited by annihilation photons, since this setup achieves the best system resolution of 120 ps FWHM.
If the trigger jitter is known and optimized at approximately 66 ps FWHM, the system resolution becomes 137 ps FWHM when only the start traces are digitized, which might be considered to be an acceptable value. This makes digitizing only the start traces a possible alternative to digitizing both the start and the stop traces.
Chapter 4

Summary and recommendations

Summary
Several setups were presented and assessed with the intention to develop a procedure that is suitable for determining scintillation pulse shapes of PET scintillation crystals, excited by 511 keV photons, with sub-nanosecond timing resolution. The emphasis was on determining the exponential rise time of the pulse.

It was concluded that the analog setup that was initially built and tested was not simple to implement with sufficient system timing resolution to determine rise times of fast PET scintillators.

As an alternative the single crystal setup was tested, which was useful in understanding how to apply the digital time pick-off method with the detectors and crystals, but was not found suitable to determine the rise times accurately either, mainly because of a blurring of the resulting pulse shape due a spread in the photon path lengths.

Finally, the dual crystal setup achieved a system resolution of 120 ps FWHM, when using the timestamps from both the start trace and the stop trace. This does meet the requirements in terms of system timing resolution, making this setup suitable for determining scintillation pulse shapes of e.g. LYSO crystals, on which it was tested. The exponential rise time of LYSO was determined to be 81 ps with an estimated uncertainty interval of [50,120] ps.

Using a setup which requires only one high sample rate digitizer to digitize only the start traces might be a viable alternative if the trigger jitter can be maintained at optimal performance, preventing time-drifts. The system timing resolution will be slightly worse than the resolution of the system using both the start and stop traces, but knowing the trigger jitter accurately allows correcting for this in the fitting procedure and finding a correct rise time. A drawback of this setup is the reduced sensitivity of the fit function to changes in the rise time parameter, adding to the uncertainty in the determined rise time.

Improving the count rate
The dual crystal setups meet the requirements in terms of the timing resolution, but they can still be improved by reducing the statistical noise. Because the histograms converge to a probability density function for increasing number of counts, the statistical noise is reduced by increasing the total number of measured events. The reduction of the noise will allow making more accurate estimates of the uncertainty of the fitted parameters and a further reduction of this uncertainty. This is very impractical using the setups described in the present work, since the count rates are in the order of at most 20 counts per minute. To measure ten times as much data as is done in this work, or more, the measurement should run for weeks, even months.

It is therefore recommended that the dual crystal setup be modified by replacing the ID100 stop detector by an array of single photon avalanche diodes (SPADs).
each with its own time-to-digital converter (TDC), as described by Niclass et al. [23], who specify 115 ps FWHM timing jitter with a 32x32 SPAD array. Under certain conditions 50 ps FWHM was claimed for the SPAD’s timing resolution, as described by Rochas et al. [24], so improvements of the detector seem possible. Using such a detector, each pixel generates its own timestamp corresponding to the detection of one photon from the scintillation pulse, which in principle is independent of the timestamps from the other pixels in the array. This would enable achieving count rates of tens or hundreds of times larger than achieved in this work, opening the possibility to acquire much more events in the same amount of measuring time, reducing the statistical noise and the uncertainty of the fitted parameters further.

**Improving the fitting procedure**

Since the bias towards early times in the dual crystal setup is visible in the falling edge and the determined decay time of the scintillation pulse, it is recommended that a fit procedure is developed that takes the probabilities of biased events into account in order to determine correct decay times, in addition to determining accurate rise times, on the basis of a dataset in the histogram which is biased.

However, if the count rate is increased, e.g. by using a different stop detector as described above, a more appropriate way for acquiring accurate decay times becomes viable, which is reducing the bias by reducing the probability to detect a photon given that there is a scintillation pulse in the stop detector (the stop-to-start ratio). If a setup can be developed this way with negligible bias and still practical count rates, this is the more favorable solution since it does not require a model to correct for the bias.

**Further work**

Since the dual crystal setup in the present state performs well in terms of system resolution, it is recommended that the setup is used to determine rise and decay times of other PET scintillation crystals, such as LaBr₃, which has a longer rise time (depending on the dopant concentration) than LYSO. This also provides a way to compare the results of the setup to other research on these numbers.
Appendix A

Analog setup

A.1 Initial setup

The very first setup that was built used analog time-pickoff and a Time to Amplitude Converter (TAC). The basic idea was to use the setup as shown in figure A.1, with the crystal in a sample holder box from which only a small amount of light would be allowed to escape towards the stop detector.

The setup uses a Timing Alignment Probe (TAP) as the start detector. This is a device which contains a $^{22}$Na source inside a plastic scintillator which is used to detect when a positron is emitted. This signal is used as a start for the TAC. The signal is first converted to a logic pulse by a Constant Fraction Discriminator (CFD) and delayed in time by a Timer unit. This is done by using an output from the Timer unit that accurately marks the end of it’s ‘signal out’, called the ‘end marker’. By adjusting the length of the ‘signal out’, the delay before the ‘end marker’ comes is adjusted.

The stop detector was a Philips XP2020 PMT with a BaF$_2$ crystal optically coupled to it’s surface. The stop pulse is produced in the exact same way as the start pulse: it has it’s own CFD and Timer unit. The only difference is that the ‘end marker’ signal is delayed a bit more by using a long cable, to assure that it never reaches the TAC before the start signal has come in.

A logic unit is used to select coincident events (an event from the TAP within a fixed coincidence window after there was an event from the PMT). This coincidence window was implemented using the same Timer unit as before, but now using the ‘signal out’, instead of the ‘end marker’ output.

The setup as described only serves to measure what the system resolution of this system would be if it were to be used to measure actual intensity pulse shapes of scintillation crystals. This is because the light collection efficiency at the stop detector is optimized (by coupling the crystal to the PMT’s surface), whereas instead the light from the crystal under study would have to be attenuated a lot to assure a
low stop-to-start ratio, to prevent bias towards early times in the histogram of the time differences between start and stop.

The system resolution was determined to be between 300 and 400 ps, which was insufficient. Therefore, a number of variations of the setup was developed and tested. These variations include

- connecting the TAP directly to the start of the TAC and the delayed PMT signal directly to the stop of the TAC. This made the timing resolution a factor of 3 or 4 worse.

- Going back to the initial setup, but without the timers to select coincident events. The stop-CFD’s energy threshold was adjusted by splitting the PMT’s signal before the CFD and sampling the energy of the events that pass the CFD’s energy threshold, then adjusting this energy threshold to reject all events below the 511 keV full-absorption photon peak. This didn’t improve the timing resolution significantly.

- Reversing the start and stop: putting the PMT at the start and the delayed TAP signal at the stop, again no coincidence selection. This setup also made the system resolution degrade by about a factor of 3.

After testing all these variations, the PMT’s resolution was tested separately by doing a decay measurement on the BaF$_2$ crystal, using the TCSPC method. For this purpose two PMTs were used with the crystal optically coupled to the start PMT, making sure that the stop PMT only sees a small number of photons per scintillation pulse on average. This did not yield the expected 0.9 ns decay time, but decay times from 1.4 ns to 1.7 ns. It was attempted to adjust the focusing of the PMT’s dynode structure, optimizing for a narrow photon peak in the energy spectrum, based on the idea that the transient time spread in the PMT would be related to that. Using this method the results of the decay time measurement of the BaF$_2$ did not improve.

### A.1.1 Laser focus adjustment

It was subsequently attempted to adjust the PMT to have an optimal temporal resolution when excited by laser, using the a small pulse width laser. It was found that it was not possible to trigger the PMT’s signal at single photons without further amplification. When it turned out that when using the additional amplifiers the PMT’s resolution still remained in the 300 ps range, it was decided to move to a whole different setup.

### A.2 SiPM and ID100

In this new setup the TAP start detector was replaced by a SiliconPhotoMultiplier (SiPM) and the PMT stop detector was replaced by an ID Quantique ID100 single photon counting device. The analog time-pickoff circuitry used in this setup is shown schematically in figure A.2. Since the results of these detectors looked promising, it was decided to try to optimize the timing resolution even further by switching towards digital time pick-off, as described in the Methods (chapter 1).
Figure A.2: Schematic of the electronics of the setup using the SiPM start detector and the ID100 stop detector, still using analog time pick-off
Appendix B

Trigger delay correction for the Acqiris DC282

Using the data from the last on third of the 300,000 events from the dual crystal setup, which digitized both traces (as described in section 2.2) a histogram of the stop timestamps was created. Since the stop signal is the signal that produces the trigger of the time trace sampling, in principle the stop timestamp (the time that the stop trace crosses an arbitrary threshold) should always be at the same time. In practice, the jitter in the trigger determines the spread in these timestamps. As mentioned in section 1.5.2, the timestamps have an arbitrary number in between 0 and 125 ps added to them, which is the trigger delay. Since the trigger delay is determined and stored for each trace, the timestamps can be corrected for this. Shown in figure B.1 are both the corrected and the uncorrected timestamps from the stop trace, while triggering on this same stop trace (in this case the trigger was connected to one of the channels that was not digitized, instead of to the ‘external trigger’ input of the Acqiris). This way, the trigger jitter is visualized and the reduction of trigger jitter by applying the trigger delay correction is also shown. It can be noted that the mean of the distribution shifts for some 60 ps towards earlier times when correcting for trigger delay and also that the distribution becomes more narrow: from 118 ps to 66 ps FWHM, which is a large improvement relatively.
Figure B.1: Effect of applying the trigger delay correction to the accuracy of the trigger. 95% confidence intervals of the fit are, for the FWHM: 0.35 ps for the corrected and 1.6 ps for the uncorrected data respectively; and for the mean: 0.15 ps for the corrected and 0.69 for the uncorrected data respectively.)
Appendix C

Trigger logics, dual crystal, dual trace setup

Shown in this appendix is the timing of the signals that are used in the dual crystal setup, digitizing both the start- and the stop trace. This setup has no possibility to read out the peak sensing ADC’s busy signal. With this setup it is therefore necessary to add some logics manually to assure that there will be no loss of synchronization between the peak sensing ADC and the time trace sampling ADC. Two measures are taken.

First there is a counter, which counts down from a preset number. This number is the number of events that should be stored in the peak sensing ADC’s internal memory before being read out by the PC. This counter has as busy out, or ‘active’ signal, which goes true as soon as the PC tells it to start counting down and it goes false after it receives the last event, which brings it’s count value to zero. The ‘counter active’ going to false then is the signal for the PC to read out the ADC and reset the counter after it’s done with the read-out. The PC loads the preset number into the counter and starts a new session of storing events in the ADC’s internal memory and counting down to zero.

Secondly there is a Veto signal needed for different reasons in two cases, as indicated in figure C.1.

- Ad. ‘Trace sampling ADC busy’ : The time that the trace sampling ADC spends ‘digitizing’ after receiving the ‘trigger in’ depends on how long the trace sampling window is and what part of that is taken from the ADC’s data buffer (since the latter part is available instantaneously).

- It can be concluded that Veto is needed for at least the response time of the ‘Counter active’ signal to go to false after the Trigger-Out signal from the trace sampling ADC goes true (case 2). In general, if there are not exclusively ‘last events’ (if the peak sensing ADC is storing more than one event in its internal memory before being read out by the PC), the Veto must be at least as long as the time that the peak sensing ADC is busy with digitizing and storing in the buffer.

- Strictly speaking, in case that the peak sensing ADC is in fact read out every single event, there are exclusively ‘last events’ and the Veto needs to be only as long as the response time of the Counter. After this time the ‘Counter active’ signal goes false until the PC is done reading out the ADC and this ‘Counter active’ could be used as a constructed ‘peak sensing ADC not busy’ signal.
Figure C.1: Overview of the timing of the triggers of the dual crystal setup, digitizing both traces (using manual ‘peak sensing ADC busy’ signal and ‘ready for readout’ signal). Low is true, high is false.

Case 1: counter receives an event which is not the last event
(Counter active remains true)

Case 2: counter receives last event which sets its value to zero

Figure C.1: Overview of the timing of the triggers of the dual crystal setup, digitizing both traces (using manual ‘peak sensing ADC busy’ signal and ‘ready for readout’ signal). Low is true, high is false.
Bibliography


