

UNIVERSIDAD DE SANTIAGO DE COMPOSTELA
FACULTAD DE FISICA
Departamento de Física de Partículas



Study of fast radiation-detectors based on fast
halide scintillator crystals and their application to
the CERN n_TOF experiment

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UNIVERSIDAD DE SANTIAGO DE COMPOSTELA

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CERTIFICA:

que la memoria titulada **Study of fast radiation-detectors based on fast halide scintillator crystals and their application to the CERN n_TOF experiment**, ha sido realizada por **María de la Soledad Robles Manzano** en el **Departamento de Física de Partículas** bajo su dirección y constituye el trabajo de **tesis** que presenta para optar al grado de **Doctora en Física**.

Santiago de Compostela, a 28 de septiembre de 2016.

Fdo. Ignacio Durán Escribano

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¹Give me five!

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"There is something breathtaking about the basic laws of crystals. They are in no sense a discovery of the human mind; they just are - they exist quite independently of us-. The most that man can do is become aware, in a moment of clarity, that they are there, and take cognizance of them."

-M.C. Escher

A mi sobrino Gabriel

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Introduction

Experimental Nuclear Physics research requires complex set-ups made of specific detectors as much accurate as possible in terms of time and energy resolution. This is the reason why new detectors should be developed, taking advantage of the continuous advances in materials and techniques, to be used for detecting light nuclei, charged particles and γ radiation produced in nuclear processes. Among the wide variety of the used detectors those based on the use of scintillation materials either plastics or inorganic crystals are of the biggest interest.

Along the middle last century many studies of the scintillation detectors have been carried out [1]. Moreover, in the last decades, the improvement of the crystal manufacturing and the new developed photodetectors has led to improvements in calorimetry, energy resolution, particle identification and time resolution.

The aim of this work was the characterisation of different nuclear detectors based on scintillation crystals, looking for their possible uses in the detection of γ radiation from nuclear processes such as nuclear fission and neutron capture, as well as to their application to the study of the background of the n_TOF facility at CERN, in Geneva, Switzerland.

Those radiation detectors based on inorganic crystals studied in this thesis work are: CeBr₃, CsI(Na) and CeF₃ scintillator crystals coupled to different photodetectors such as new photomultiplier tubes and PIN diode. In addition to this, very fast plastic scintillators were used to provide ultra-fast coincidences in order to discriminate charged particles from γ -rays. These detectors have been tested both in the detector development laboratory at the Santiago de Compostela University (USC) and in the n_TOF facility at CERN.

Thesis structure

Chapter 1 explains the main problems found when using fast detectors, particularly fast scintillator detectors, proposing a number of solutions, to overcome the detected difficulties both in the hardware and in the software. Some hardware solutions, such as the design of a shaping stage, a modified voltage divider to adapt the dynodes of a photomultiplier, as well as a set of software algorithms to perform Pulse Shape Analysis (PSA), have been specifically developed for this work.

Chapter 2 starts by the fundamentals of the scintillator detectors and contains the description of the fast scintillator detectors used in this work. The simulation work on the scintillator crystals, CeBr_3 and $\text{CsI}(\text{Na})$, are included as well. The γ -rays detection efficiency and the expected deposited energy by β -particles were obtained by the study of the simulation results.

In Chapter 3 are presented the results from the tests done at the GENP-USC laboratory after adopting solutions to cope with the problems discussed in Chapter 1. The obtained energy resolution and linearity, the time study as well as the PSA devoted to each detector are discussed.

Chapter 4 is dedicated to the measurements performed at the n_TOF experiment at CERN. A description of the facility is firstly given, followed by the results obtained when the scintillator detectors were set in the n_TOF experimental area in order to detect prompt γ -rays from radiative neutron capture reaction, (n,γ) using ^{197}Au and ^{nat}Ag samples. Then the prompt γ -rays from nuclear fission induced by neutrons were measured for the $^{235}\text{U}(n,f)$ reaction, in coincidence with a PPAC fission detector. Last section contains, the analysis of the γ -flash effect and its characterisation using the scintillators studied in this work, together with other fast detectors used by the n_TOF collaboration.

Finally, the main conclusions are presented, suggesting further uses of the techniques here exposed.

Additional information concerning electronics designs and simulation work is added in Appendices A-G at the end of this work.

1. Hardware and Software solutions for fast scintillator detectors

In the quest for higher accuracy in the nuclear experiments, modern detectors and modern digitizers are often dealing with fast signals close or beyond 1 GHz, having a rise time lower than 1 ns. Thus, when developing the corresponding experimental set-ups, special care must be taken with these fast signals in order to hold all their available information. Particularly, concerning the shaping and the transmission of the electrical signals, more sophisticated rules than the elementary Ohm's Law are needed to simulate and improve these requirements. After Heaviside, it is commonly known that electronic components may be characterised through their resistance, capacitance and inductance being a complex impedance function of the signal frequency. However, the full Maxwell-Heaviside equations are not only hard to deal with, but sometimes non-useful, as the electronic components have not an easily known complex impedance. Its highest frequencies damping is not linear and, moreover, they are embedded in their environment that produces spurious parasitic impedances being almost impossible to characterise.

Nowadays, the CAD tools allow to reproduce in a quite realistic manner the behaviour of electronic components, but its environment is still difficult to model. Moreover, as every detector shows some specific constraints, a try-and-see method should be required and so some intuition is needed when looking for the optimal solution. In the following sections the main characteristic parameters of fast detector signals are mentioned and the software and hardware solutions adopted for the detectors used in this thesis work are described. The here used definition of the main characteristics of a pulse signal are given in Appendix A [2].

Problems related to very fast scintillator crystals coupled to PMTs.

Some scintillation crystals recently becoming widely used, as, for instance, Lanthanum halides, BaF_2 or CeBr_3 , have a huge Light Yield (L.Y.) with a very fast main component. When coupled to high-Q.E. (Quantum Efficiency) and high-gain Photomultiplier Tubes (PMTs), a very high current-peak associated with the rising edge of its scintillation flash is produced. This current peak is, in these cases, very short in time (< 1 ns) and can be more than two orders of magnitude larger in amplitude than in typical former scintillators. This is a challenge for the traditional Voltage Divider (VD) in the PMTs, making non-linear its response and creating a problem to the forward signal processing chain.

The standard VD is made of passive components as a chain of resistors and some biasing capacitors. The HV at one of the ends of the resistor chain assures a given potential difference between every couple of consecutive dynodes (inter-stage voltage) and the actual value of the whole resistor's chain defines its steady current flow. A peak of current originated by the fast component of the high crystal L.Y. produces a sudden change of the bias voltage in the dynodes chain. This change is, obviously, larger in the last dynodes where the inter-dynode electron swarm increases as due to the multiplication factor at every dynode. This potential-drops at the last dynodes produce a feed-back effect in the first ones that leads to a deviation from the linear behaviour of the PMT's gain. On the other hand, the electron swarm, when going from the last dynode to the anode, creates a distortion of the electric field, leading to a dramatic miss-function of the whole PMT that remains unable to reproduce the original shape of the scintillator L.Y. This is a well known problem, having known remedies for pulses wider than a few nanoseconds. But narrowest pulses or more generally, those having a rise time of the order of one nanosecond, become more challenging, requiring specific solutions.

On the other hand, these pulses, so short in time, create specific problems when analysed by the standard spectroscopic chains, that were designed to deal with signal timings of the order of few microseconds. The output signal provided by the scintillator detectors used in this work does not match the specifications of the standard spectroscopic chain, leading to undesirable non-linear effects, as it will be described in detail in Chapter 2. In Fig. 1.1 such effects can be appreciated, comparing three different

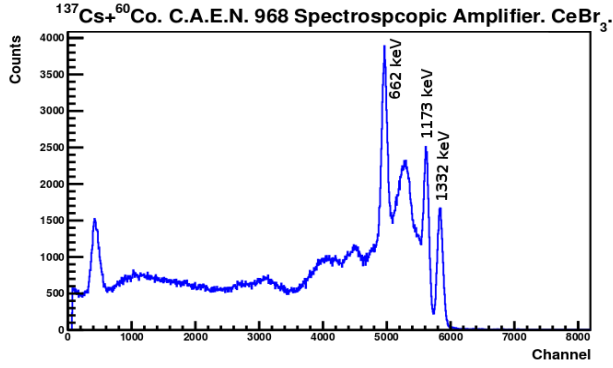
shaping amplifier (SA) modules¹. It can be seen how the spectra of the energy deposited by different radioactive sources are not correct, as the higher energy peaks appear at channels lower than expected. In Fig. 1.1, (a) a clearly non-linear effect is shown, resulting in the subsequent distortion of the shape of the photopeaks, and consequently of their FWHM; in such a case the Eq. 1.2 will provide wrong values of the energy resolution. In spectra (b) and (c) the most energetic peaks, $E \geq 1 \text{ MeV}$, do not appear in the spectra, showing up instead a peak that corresponds to a saturation of the SA. It is worth mentioning that such non-linearity has been reported by previous authors, even suggesting to apply non-linear corrections instead of solving the problem. Moreover, this effect is also found not only in analog standard spectroscopic chains, but also in digital sampling systems where the linearity of their input amplifiers should be not guarantee for frequencies beyond the GHz. In the following Sections are described the different solutions taken into account along this Thesis work, to deal with these different problems found when using fast scintillator detectors.

Problems produced by fast signals in cables and Front-End Electronic, FEE. The main effect produced in cables are the non-linear signal attenuation and a worsening of the Signal-to-Noise Ratio (SNR). Obviously, the longer the cable, the worst the SNR will be. Firstly because of the attenuation of the Very High Frequency (VHF) components, and secondly because the antenna effect makes cables to be a source of noise, even if coaxial ones were used.

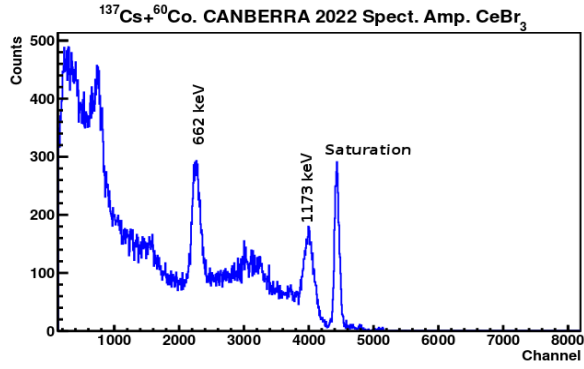
The electrical specifications of cables and connectors gain relevance in the propagation of the signal in an appropriate way, i.e., keeping linearity in both frequency and amplitude. Most of the coaxial cables used in the nuclear experiments have losses that are bigger at the higher frequencies. That means that signals whose rise times were less than a few nanoseconds should be affected and the losses along long coaxial cables will be larger.

Signal attenuation and deformation are produced by the non-linear be-

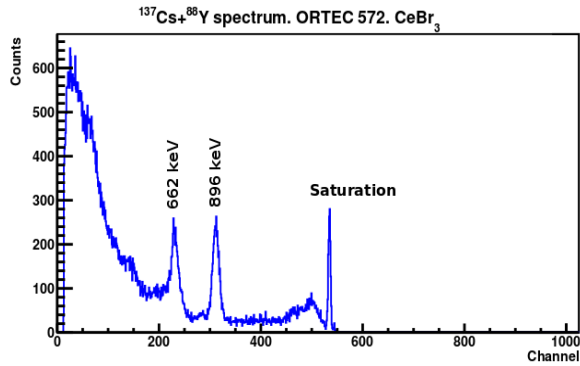
¹CANBERRA Mod. 2022 [3], C.A.E.N. Mod. 968N [4] and ORTEC Mod. 570 NIM modules [5]. The ACQ system consisted of a Multichannel Analyser (MCA), mod. 8000A from Amptek Inc [6].



(a)



(b)



(c)

Figure 1.1.: Non-linear behaviour of $^{137}\text{Cs} + ^{60}\text{Co}$ ((a) and (b)) and $^{137}\text{Cs} + ^{88}\text{Y}$ (c) spectra, measured with different standard spectroscopic amplifiers without suited signal conditioning.

haviour of the cable impedance, being actually a complex function of the signal frequency spectrum. The wire resistance is affected by a spurious inductance and the capacitance by the non perfect dielectric that insulates the wire and the grounding mesh. Actually, the insulator is made of a material having a non-linear behaviour, neither in frequency nor in amplitude, in such a way that the cables nominal capacitance appears as having a non-linear complex impedance to ground (in a similar way as explained for capacitors in Appendix C), degrading so both the amplitude and the shape of the original signal. The specifications of cables and connectors must so match the shaping of the fast-detector output, and SubMiniature Version A (SMA) coaxial RF cable standard connectors and cables must be used instead of LEMO or BNC standard ones, when required. Once again, the advantage of dealing with signals from the detectors not having frequency components above few GHz becomes obvious.

A second effect due to coaxial cables is the fact of they are linking the ground of both the sending signal system and the receiving one, and so all the current flowing in one direction through the signal wire must return via the cable ground mesh. This is specially relevant when dealing with a huge number of fast signal channels, because they produce peaks of current that disturb the ground system. Of course, the higher the frequency of the signal is, the more severe are the problems created in the ground systems. A commonly proven solution is the use of twisted-pair cables where both wires are floating and so there is no ground links. Moreover, in the twisted-pair configuration, both wires are picking-up the same noise, that cancels when reading it in a differential mode. The use of HF twisted-pair cables is highly recommended, as far as possible.

Problems observed when digitising fast signal using flash-ADC acquisition. Once the best-shaped analog signal arrives to the front-end data acquisition system, flash analog-to-digital converters, onwards fADC, are the faster way to digitise it. Based on a cascade of in parallel comparator circuits whose number is determined by the resolution given by the number of bits (8-10 bits in the most of the cases) are suitable for applications requiring very large bandwidths. Considerable power consumption, low resolution and higher cost may be considered as their main disadvantages.

The sampling frequency, f_s , of the fADC must agree with the Nyquist-Shannon sampling theorem (see Ec.1) in order to reproduce the analog input signal with a frequency f_H , as closely as possible.

$$f_s > 2 \cdot f_H \quad (1.1)$$

The major problem when analog signals are to be digitised, concerns the sampling of the high frequency rising flanges (either the one corresponding to the signal or to the noise spikes): a poor sampling frequency means few number of samples to reproduce the critical part of the input signal and thus, increases the uncertainty of the rise time measurement [7]. Therefore, fast signals having a rise time of a few nanoseconds, require sampling frequencies above many hundreds of MHz or GHz.

The number of bits to quantify the signal amplitude is also crucial to reduce the uncertainty of the off-line analysis of the digitised signals. The more the number of bits, the lesser the uncertainty will be. In the particular case of signals coming from a radiation detector, a scarce quantisation of the signal amplitudes means a loss of energy resolution, which is related to the height of the signal.

On the other hand, if the analog signal to be digitised comes from a fast PMT detector, whose frequency associated to the rise time were comparable to the f_s given by the fADC, a signal smoothing should be a solution, decreasing so the rise time frequency. This smoothing can be sometimes simply done by passive components in the detector output cable what will produce a slight signal integration, but care must be taken with matching the impedance of the coaxial cable.

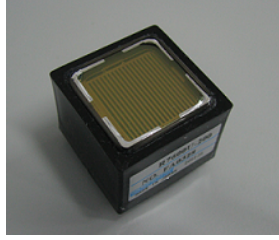


Figure 1.2.: PMT mod. R7600U-200 from Hamamatsu.

1.1. Hardware solutions

The challenge of dealing with a very high current peak produced in the optodevices by high-performance fast-scintillator crystals, requires specific hardware solutions. Concerning PMTs (see Fig. 1.2 where a generic PMT is depicted), it was already commented the relevance of managing the high and abrupt peaks of current generated in the dynode chain and, therefore, the design of the VD chain is crucial for the signal fidelity regarding the original scintillator shape. Furthermore, the sooner the signal is well-shaped without losing information on the relevant observables, the lower the undesired effects should be produced in the rest of the front end electronic chain.

The first temptation one has when dealing with such a fast crystals is lowering the HV in order to reduce the gain of the PMT. But reducing the gain results, in any case, in a reduction of the spectroscopic resolution that, sometimes, balance out with the obtained gain in linearity. If the HV reduction is severe both resolution and linearity deteriorate by the fact of a bad focusing of the photo-electrons in the first stages. Some PMT manufacturers suggest to use a tapered distribution of the VD resistors chain (see Appendix B) improving so the attained linearity (see Fig 1.3.) A solution allowing a wider range of gain control without de-focusing the first stage is to set a Zener-diode in the first link of the VD chain, instead of a resistor. Furthermore, PMT manufacturers produce active chains, having transistors in the three last links of the chain, improving so its dynamic range. Some users decide to pick-up the signal from the next to last dynode and reducing in consequence the loading resistor at the anode,

leading so to a better behaviour of the electron swarm in the last stage. Finally, there is the possibility of using an active circuit to reduce the gain in the last stages when a big scintillation is detected in the first ones.

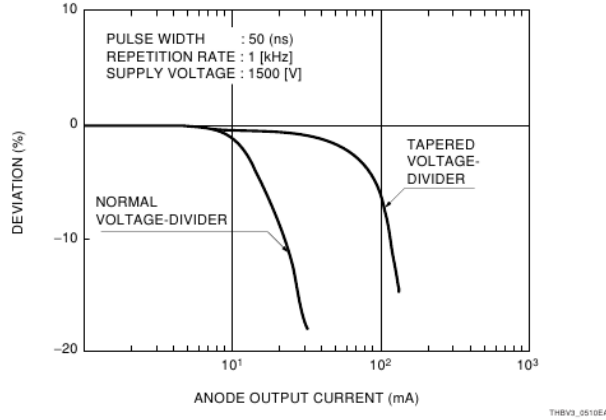


Figure 1.3.: Deviation from linear behaviour in normal and tapered voltage divider circuits. The linear response is maintained for one order of magnitude more for the tapered design. Courtesy of Hamamatsu Photonics K.K.

Most of these remedies achieve very limited success when the raising edge of the scintillation is lower than 1 ns and very often create a ringing effect in the rest of the pulse.

An easy solution, used in this work with the CeBr₃ crystals, is to modify the VD in order to reduce the voltage in the last stages without changing it at the first ones (see Appendix B) and, besides this, reducing the HV in consequence to get a gain's reduction without affecting the focussing potential at the first dynode. In addition to this, when dealing with ultra-fast crystals, a commonly useful trick is to set a capacitor in parallel with the load resistor, acts reducing the impedance of the anode's load mainly for the higher frequencies and producing a positive effect when suitably dimensioned. As a first advice one must refrain from using components in the VD (neither resistors, capacitors, diodes nor transistors) not being specified for frequencies well beyond the GHz range (normally, the SMD components used in fast electronics are compliant with, but most of the

resistors and capacitors found in the shelves are not). Should the appropriate capacitors should be used (see Appendix C); the firstly observed effects are the slowing down of the rise time and the reduction of the peak amplitude. These effects seem to worsen the quality of the output pulse (both time and amplitude resolution should be affected) but this is not the case when both the extremely short rise time and the extremely high amplitude are creating a bigger trouble. In fact, the finally got time resolution depends on both the rise time and the time-resolution of the Front End Electronics (FEE), in such a way that sending extremely fast signals to the FEE, paradoxically, does not result in a better time resolution and results in a poorer energy resolution. This is partly due to the fact of the higher frequency components of the signal not being well managed neither by the cables nor by the FEE. Concerning the amplitude of the pulses, the use of a well suited capacitor does not entail a loss of information on the energy deposited in the crystal, because the PMT's output is a current signal and all the charge integrated in the capacitor is always given back, provided that low loss HF components are used. Should the RC time constant well adapted to the signals we are dealing with, both time and amplitude resolutions rest undamaged.

1.1.1. Voltage Supply Network

PMTs having a high Q.E. and a high gain, when coupled to the high L.Y. CeBr₃ crystals, produce very high current peaks because of its short rise time and very fast decay component (see Table 2.1) that create a huge number of photoelectrons in the photocathode in a very short period of time. As it was above commented, the gain at the last dynode stages saturates, leading so to a degradation in the output linearity. In order to cope with this problem a new VD was designed as it is described in the Appendix B. To assure a low SNR, this development was done doing a minimal handling on commercial D Type Socket Assembly Normal Divider mod. E5996 from Hamamatsu [9].

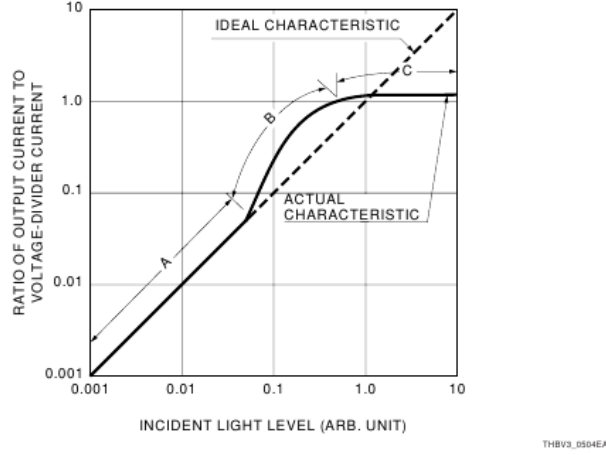


Figure 1.4.: Response curve of a PMT as a function of the Light Yield. Ideally the response is linear, shown with a dashed line. The solid line shows the non-linear relation for high Light Yield. (Figure courtesy of Hamamatsu Photonics K. K. [8]).

1.1.2. Spectroscopic chain measurements

In nuclear physics experiments, besides simply detect certain events (counters), one could need to measure some specific observable magnitudes such as, for instance, the time (timers), the deposited energy (spectroscopic analysers), the signal shape (Pulse Shape Analysers, PSA), or any combination of them. The electronic pulses must so be adequately handled in order to preserve its characteristics related to the observables of interest.

When dealing with spectroscopic analysers, a typical set-up consists of mainly five different stages: the detection system, the preamplification stage, the shaping amplifier, the spectroscopic amplifier (SA) and the acquisition system, as sketched in Fig. 1.5.

A detector produces typically either a voltage or a current signal (see Refs. [2, 10]) but very often something intermediate, and so the preamplifier must be specifically chosen to match the detector output. Typical voltage signals should be coupled to an extremely high-impedance input amplifier whereas typical current signals will require a low-impedance in-

put to drain the charge produced by the detector. Commonly, the output impedance of the detector is a complex impedance and so the preamplification stage can be seen as an active filter, adapting the input/output impedances (transimpedance). It must be placed as close as possible to the detection system to avoid unwanted effects due to the stray capacitances of cables. Shaping amplifiers are used after the pre-amp stage to further amplify the signal but modifying its shape in order to make it well suited for the rest of the FEE. Finally, the SA's, on top of its amplitude gain, manage parameters such as the polarity, the time, the final shape, and performing a baseline restorer in order to condition it for the downstream ADQ system that usually consists of either a MultiChannel Analyser (MCA) or an Analog to Digital Converter (ADC), as it will be shown in Chapter 3 and Chapter 4.

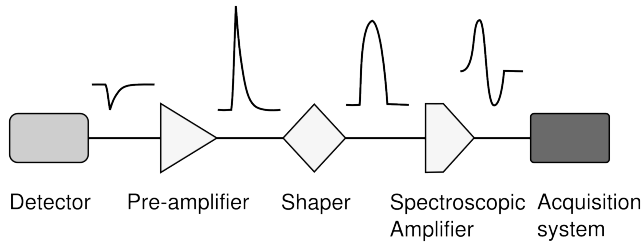


Figure 1.5.: Typical measurement chain for measuring the deposited energy, called spectroscopic chain. It consists of five stages: the detection system, the preamplifier stage, the shapery amplifier, the spectroscopic amplifier and finally, the acquisition system. The evolution and modification of the signal is schematically represented in the line.

1.1.2.1. Non-linearity effects

To overcome the problem of lack of linearity when the time characteristics of the analog signal from the detectors were not matching the specifications of the SA and the MCA, a hardware solution is proposed.

Since the observed non-linearity effects are due to a problem of signal conditioning, the characteristics of the output signal from the optodevices, coupled to its corresponding scintillator, must be managed to cope with the

specifications of the spectroscopic amplifier (SA); therefore, when designing the electronic chain, an specific shaping stage must be implemented.

The spectroscopic amplifier chosen for that purpose is the CANBERRA Mod. 2022 whose main requirements for the input signals are [3]:

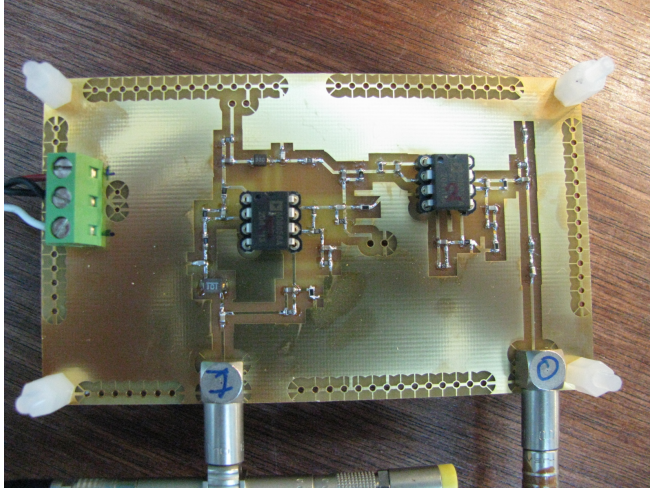
1. Signal polarity: positive or negative pulses.
2. Rise time less than shaping time chosen: $<0.5 \mu\text{s}$, $1 \mu\text{s}$, $2 \mu\text{s}$, $4 \mu\text{s}$, $8 \mu\text{s}$ or $12 \mu\text{s}$.
3. Decay time larger than $40 \mu\text{s}$ for $0.5 \mu\text{s}$, $1 \mu\text{s}$, $2 \mu\text{s}$, $4 \mu\text{s}$, $8 \mu\text{s}$ or $100 \mu\text{s}$ for $12 \mu\text{s}$.
4. Amplitude $\pm 10 \text{ V}$ divided by the selected gain for linear response.

About the output signals from both $\text{CeBr}_3\text{-PMT}$ and CsI(Na)-PMT scintillator detectors, it is noticeable that their both fall times, around 30 ns and 600 ns, respectively, are below the minimum value specified in the requirement 2.

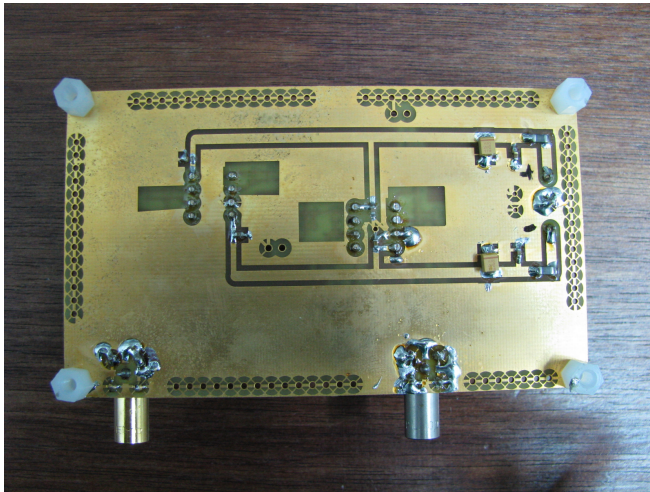
Stretcher PCB design To be consistent with all the above mentioned, the following considerations were taken into account when designing the shaping circuit, in the following called *Stretcher PCB*:

1. The conditioned signal must maintain proportionality to the observables of the initial signal.
2. The decay time of the conditioned signal must be larger than $40 \mu\text{s}$.

The designs of both *Stretcher PCBs*, one for $\text{CeBr}_3\text{-PMT}$ and another for CsI(Na)-PMT , were simulated using the software package OrCAD 10.5 [11] including, among other programs, PSpice, Capture CIS and Layout Plus. The components quality must be suited for the high frequencies of the initial signal and the subsequent ones (see Appendix C). Fig. 1.6 shows the *Stretcher PCBs* for $\text{CeBr}_3\text{-PMT}$ detector and a detailed explanation of the designs can be found in Appendix D).



(a)



(b)

Figure 1.6.: *Stretcher* PCB for CeBr₃-PMT detector. (a) Top layer, (b) Bottom layer.

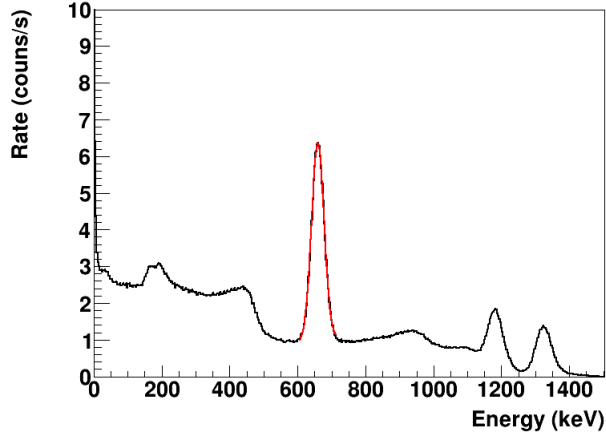
Concerning the energy resolution, it is customary defined as:

$$R(E) = \frac{FWHM}{E} \times 100 \equiv \frac{2.35\sigma}{E} \times 100 \quad (1.2)$$

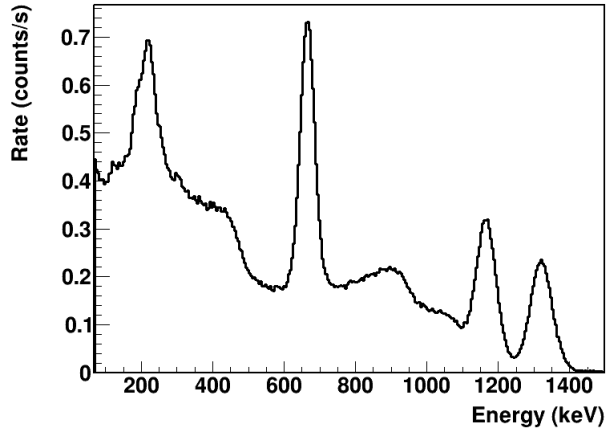
where E is the energy deposited in the detector and the Full Width High Maximum (FWHM) must be given in the same units as E being related to the standard width of peaks having a Gaussian shape, as it is most often the case of the spectra peaks from radioactive sources, after background subtraction.

Non-linear spectra will provide wrong energy resolution values. Therefore, good linearity is needed to provide an accurate value of the energy resolution and a specific signal conditioning is crucial to an appropriate characterisation of the response of the scintillator detectors in terms of resolution and linearity.

Two different *Stretcher PCBs*, for CeBr_3 -PMT and $\text{CsI}(\text{Na})$ -PMT, were done to solve these problems, conditioning the output of the scintillator detectors by taking into account the requirements of the SA. Both *Stretcher PCBs* provide signal linearity after passing the SA, solving so the problem discussed previously. The ^{137}Cs and ^{60}Co spectra produced by CeBr_3 -PMT and $\text{CsI}(\text{Na})$ -PMT respectively are shown in Fig. 1.7, where non-linear effects presented in Fig. 1.1 have been solved.



(a)



(b)

Figure 1.7.: $^{137}\text{Cs}+^{60}\text{Co}$ acquired using the *strecherPCBs* for signal conditioning of CeBr_3 -PMT, (a), and CsI(Na) -PMT, (b). The non-linearity problems were solved.

1.1.3. Attenuator design

Into the frame of this thesis work, when trying to disentangle the n_TOF γ -flash puzzle (described in Chapter 4, the scintillator crystals were often exposed to the neutron-beam halo radiation. At these points, a very wide energy spectrum was detected due to both γ -rays and charged particles, mostly related to the spallation target γ -flash very often piled-up, that produce big scintillation signals and giving so huge signals at the PMT's output. At n_TOF, the acquisition systems had an acquisition end-of-scale up to 5 V, maybe 10 V, that implies the amplitude of detector signals very often overshoot this amplitude barrier.

A solution to these drawbacks is presented in this section, proposing the hardware design of an attenuator based on two fast Zener diodes, model DZ2W047 manufactured by Panasonic [12]. The main characteristics of this electronic component is its ability to behave as an extremely high impedance for signals whose negative voltage amplitude is comprised, nominally, between 0 and -4.7 V, having at this voltage a sharp knee, breaking its impedance down to a low and almost constant value.

The system acquisition available in the n_TOF experiment have the characteristics to choose the sampling of the ADCs. The design proposed can be seen in Fig. 1.8.

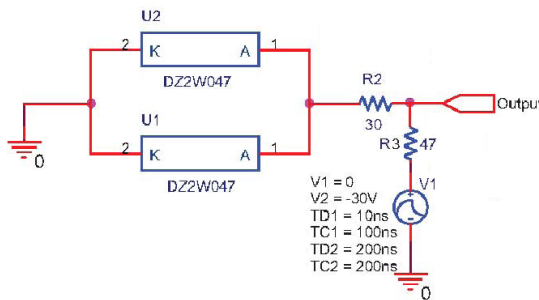


Figure 1.8.: Attenuator design based on Zener diode mod. DZ2W047 from Panasonic.

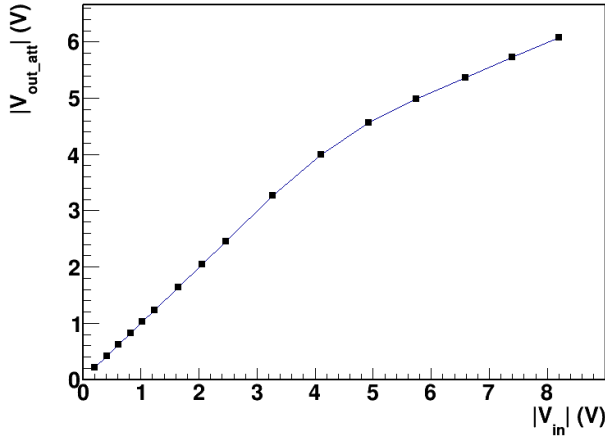


Figure 1.9.: Amplitude of simulated output signal of the attenuator based on Zener diode depending on the pulse height input signal for CsI(Na)-PMT scintillator detector

The main advantages of such design are:

1. A slightly shaping of the rise time, increasing so the number of samples of the digitised signal acquired by the fADC, improving the further pulse analysis.
2. Signals showing amplitudes above the Zener breakdown are attenuated, as it will be explained in Section 4.4.

The design was simulated using PSpice program in the OrCAD 10.5 framework. The input pulses were simulated by a double exponential voltage source: a rise exponential function of 10 ns and then a decreasing exponential function of 200 ns. These parameters of the simulated source were chosen in order to match the output signal for the CsI(Na)-PMT scintillator detector. The attenuation effect is observed, in Fig. 1.9 showing the relation of the output pulse height and the amplitude of the input signal. The results of the actual operation of the attenuator are shown in Chapter 4.

1.2. Algorithms for digital signal processing

The digital information of the pulses stored by flash-ADCs has to be accessed and analysed in a systematic way, in order to extract its useful information. This is usually done off-line, and, for that purpose, pulse shape analysis (PSA) algorithms are widely used. Output of these programs are, for instance, the digitised pulse area, width, amplitude or time of arrival, after dealing with baseline shifts and noise.

1.2.1. Raw signal analysis

PSA methods can be classified following a simple criterion based on whether signal was conditioned or not. The later are the so-called raw signal algorithms and the most common procedures for such an analysis are based on the direct comparison to known waveforms. The former methods are based on signal conditioning, often called filters, for simplicity. That means that the recorded waveform undergoes a transformation which enhance certain properties of the signal, sometimes at the price of others being reduced. The most common filters are clasified in two groups: the Finite Impulse Response (FIR) and the Infinite Impulse Response (IIR) filters. FIR filters are well defined in time and its response is finite but in the other case, the presence of feedback can lead to an infinite response function or oscillation. This work will be focus on FIR filters.

The raw signals produced in radiation detectors contain information about the incident radiation and the definition of observables, such as the pulse height, the rise time or the pulse area, becomes of interest when asking the ability of the detector to resolve, for instance, the time of arrival, the deposited energy or the pulse shape of the raw signal, that varies depending on the kind of the incident radiation because of the interaction type with the detector material.

Normally, the intrinsic noise induced in the detector and the conditioning electronics worsen the SNR, leading to complicate the analysis of the original signal. The FIR filters described below help to improve the SNR ratio still conserving the information on the raw signal observable.

1.2.2. FIR filter

Digital filtering of discrete-time signals is done by performing a discrete convolution of the general form:

$$y[n] = (f * g) = \sum_{m=-\infty}^{\infty} f[n - m] \cdot g[m] \quad (1.3)$$

where f is the convolution function, commonly called *kernel*, and g is the input. Concerning FIR filters, function f is replaced by a set of N coefficients, h_i , being N a natural number that defines the order of the filter. These coefficients dictate the weight of every sample included in the order of the filter and thus, the result of the FIR filters convolution is as follows:

$$y[n] = \sum_{i=0}^N h_i \cdot g[n - i] \quad (1.4)$$

As a general property of a convolution with a normalised function, the area of the original signal is not affected, but its shape and amplitude are modified, as well as its position in the Y-axis. The choice of the order of the filter (i.e. its width) must be made taking into account the number of samples of the entire digitised signal. In case the number of samples is comparable to the order of the filter, the output becomes reduced in samples, having $N-n$ samples, and the information contained in the signal might be blurred.

The choice of the values of the coefficients and their sign, defines different filter types and behaviours. For instance, two filters whose absolute values of the coefficients are the same, but their sign are opposite, may implement either an integrative or derivative effect. In the following, some of such FIR filters are going to be introduced.

Moving Average Filter The moving average filter is one of the most simple FIR filters. It operates by averaging a specific number of samples (bins), related to the order of the filter, of the digitised signal.

$$y[n] = \frac{1}{L} \sum_{i=0}^{L-1} g[n+i] \quad (1.5)$$

Seeing Eq. 1.5, the moving average filter is a convolution of the digitised signal with a rectangular pulse having an area of one; it may be implemented by taking a L number of forward samples to calculate the filtered signal, reducing so by L the final number of samples. Another option is to take for the i_{th} sample the same number of samples backward and forward, what implies an odd number of coefficients. This is commonly called symmetric moving average filter. When a symmetric moving average filter of L_{th} order is applied to a signal consisting in one single point of amplitude one over a zero background, the result is a squared signal of amplitude $1/L$ and a width of L (see Fig. 1.10). When it is applied to a step function of a unity height, the result is a straight slope centred at the step rise point.

Triangular smooth. A useful variant to the former average filters are the Triangular or Bartlett FIR filters, that are commonly applied as a way to smooth signals or spectra that present high frequency noise (see Fig. 1.11). The most commonly used triangular filters are the 3rd and 5th order, but the 7th order or higher can sometimes be suited. The Bartlett filters imply a set of L coefficients that scales as a triangle, in steps calculated according to Eq.(1.6) where, in order to assure a unit-gain, the sum of the coefficients results to be equal to one.

$$\frac{1}{(\frac{L-1}{2} + 1)^2} \quad (1.6)$$

A remarkable feature of these filters is its possible recursive application, twice or more, that results in a higher smoothing trending to a Gaussian filter kernel, as it can be seen in Fig. 1.10

For instance, in a Bartlett filter of order L=3, each point of the original signal is substituted by its own value divided by two, plus the values of its adjacent points divided by four.

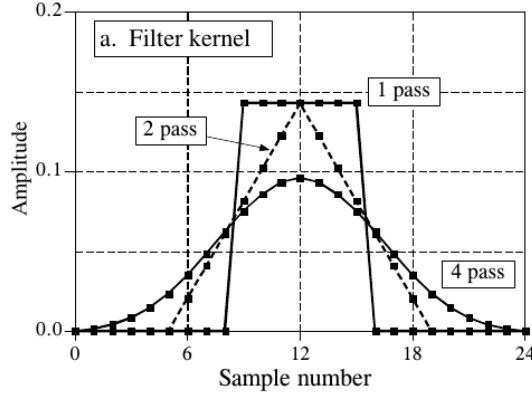


Figure 1.10.: Filter kernel when a 7^{th} order filter is passed over the digital signal once, twice and four times. Note the trending to a Gaussian kernel [13].

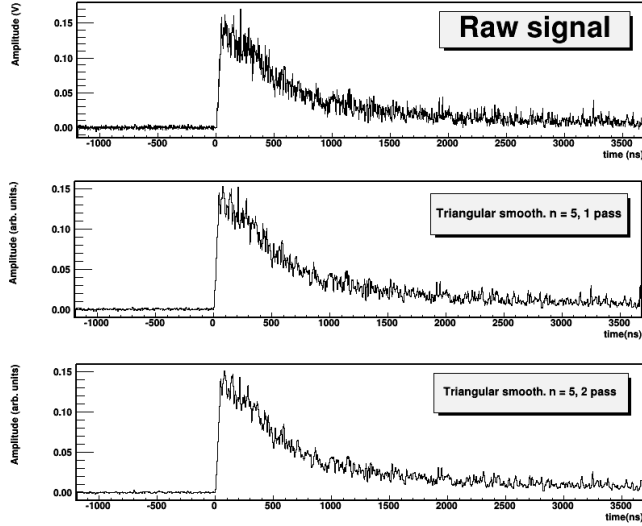


Figure 1.11.: Signal smoothed by a 5^{th} order triangular filter. The raw signal is shown in the first canvas. 1 pass filtered in second canvas. 2 pass filtered in third canvas. Note the smoothing of the shape as the number of passes increases.

Trapezoidal filter This filter is called trapezoidal due to the shape of the resulting output when it is applied to a step function. The filter is formed by two moving average filters of opposite sign separated by a time gap, G , (see Eq. 1.7). This filter is very useful to characterise signals affected by pile-up or having a not well defined baseline. It must be tailored to condition signals of specific shape and the gap G is chosen usually shorter than the rise time of the signal to be filtered; the length L must be suited to average the noise fluctuations.

$$y[n] = \frac{1}{L} \left(\sum_{i=0}^{L-1} g[L + G + n + i] - \sum_{i=0}^{L-1} g[n + i] \right) \quad (1.7)$$

Hann filter The Hann (or Hanning) filter has a sinusoidal shape, a good frequency resolution and can be used in most cases because of its good continuity properties that reduces the spectra leakage. The Hann filter may cause a distortion of the initial signal and therefore some corrections should be done to obtain an accurate result [7, 14].

The coefficients of a Hann filter

$$f(t) = \frac{1}{2} + \frac{1}{2} \cos \left(\frac{2\pi n}{N-1} \right), \quad 0 \leq n \leq N \quad (1.8)$$

1.3. Conclusions on the hardware and software solutions proposed

The high-frequency signals produced by fast scintillator detectors must be handled taking into account the problems related to the actual bandwidth of the digital signal processing and by the acquisition system used. For high L.Y. crystals, the photodetector output must be adapted to avoid saturation problems and, therefore, in this thesis work it has been introduced modifications of the original VD in order to adapt the PMT dynamic range to the high amount of light produced by CeBr_3 crystals. The inter-dynode voltages of the PMT were modified by simply adding a few components in parallel to the original ones. To obtain an accurate energy resolution, an appropriate signal conditioning is required and so two electronic circuit,

one for CeBr₃-PMT and one for CsI(Na)-PMT, have been designed and developed. To avoid saturation problems in fADC systems when signals overcome the input signal amplitude accepted by the system, an ad-hoc attenuator were designed and tested. The simulation, measurements and results obtained indicate that the solutions proposed solved the problems found when dealing with fast scintillation crystals. In the next chapters will be show that good linearity response of the detector in terms of energy resolution, calibration and non-saturation were obtained, after having adapted appropriately the signals to the requirements of the acquisition systems.

2. Scintillator detectors

Scintillator detectors are based on the property of some kind of plastics and crystals of producing and transmitting light when energetic charged particles slow down by ionising or exciting its electronic states. It is worth to recall that energetic enough photons (X- or γ -rays) can also produce free electrons, being in this way detected inside the scintillator volume. The amount of subsequent scintillation-photons depends so on the total energy deposited by the incident radiation, being the dynamics of the secondary processes depending also on the radiation's kind, and so, leading to different shapes of the scintillation pulse. A deep analysis of these pulse parameters will give the access to valuable information about the original physical processes.

To a better understanding of the results of the measurements performed in Chapter 3 and Chapter 4 is needed to bear in mind the basics principles of the radiation interaction in matter and of the scintillation processes. For a deeper comprehension of the detectors used in this work, a realistic Monte Carlo simulation of the deposited energy by both electrons and photons is also included in this Chapter.

2.1. Interaction of radiation with matter

The energy loss due to collisions with electrons by a charged particle in a given material, also called stopping power, was firstly calculated classically by Bohr [15] and the Bethe's theory included then corrections for quantum effects [16]. This theoretical formula, depending on Z , the electron density of the stopping material and a parameter, I (called "mean excitation potential"), was successful but showed deviations from the experimental data, at energies below around 200 keV. Bloch [17] introduced corrections, leading to the so called Bethe-Bloch formula, even though that further

corrections have been introduced later (see Appendix E).

2.1.1. Energy loss by heavy charged particles

Heavy charged-particles lose their energy mainly by the Coulomb interaction with the bound electrons of atoms of the material. In such interactions, the atoms can be either excited or ionised, depending on the energy of the charged particle. In the region of interest of this work, the ionisation process is dominant, as the energy of the incident particle is much larger than the bound energy of the atomic electrons.

The Bethe-Bloch formula describes well for $0.1 \leq \beta\gamma \leq 1000$ the mean energy loss of charged particles in intermediate Z materials, with an accuracy of a few percent. In Fig. 2.1, the mass stopping power for positive muons, μ^+ , in Cu is plotted as a function of $\beta\gamma = p/Mc$. Below the lower limit, $\beta\gamma < 0.1$, the velocity of the particle is comparable to the atomic electron "velocities", and above the upper limit, the radiative effects become relevant. Note that particles with $\beta\gamma \sim 3$, the minimum value of the stopping power formula, are called "minimum-ionising particles" or by its acronym, mip's. In practical cases, most relativistic particles (e.g., cosmic-ray muons) have mean energy-loss rates close to the minimum [18].

2.1.2. Energy loss by electrons

The two main processes observed when electrons (or positrons) lose their energy interacting with matter are: collisions with other electrons in the material and, on the other hand, Bremsstrahlung. It is important to understand that the electrons tracks become straggly, as their mass is small, and so the corresponding Bethe-Bloch formulas are given for the linear mean path, instead of for its actual straggled one. Therefore:

$$\left(\frac{dE}{dx}\right)_{tot} = \left(\frac{dE}{dx}\right)_{coll} + \left(\frac{dE}{dx}\right)_{rad} \quad (2.1)$$

The energy lost by electronic collision is roughly given by the Bethe-Bloch formula in Eq. E.3, however, it should be modified because two reasons: the small mass of electrons (which means that can be notably

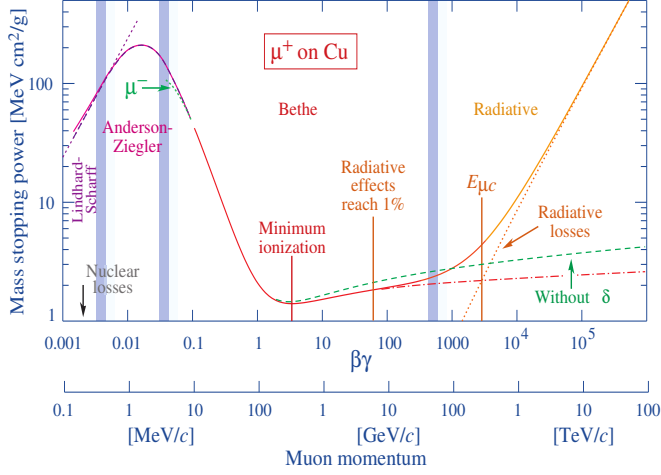


Figure 2.1.: Mass stopping power of positive muons on Cu as a function of $\beta\gamma$ [18].

scattered in the matter on the contrary of heavier charged particles) and the fact of dealing with collisions between indistinguishable particles. Taking into account these two reasons, the linear Bethe-Bloch formula leads to:

$$\left(\frac{dE}{dx}\right)_{coll} = -K \frac{Z}{A} \frac{1}{\beta^2} \left[\ln \frac{m_e \beta^2 c^2 \gamma^2 T}{2I^2} + F(\gamma) \right] \quad (2.2)$$

where T is the kinetic energy of the electron and the function F is a correction factor different for electron or positrons.

The Bremsstrahlung energy-loss mechanism is created by the Coulomb field of the nuclei, resulting in the emission of braking-radiation. The linear specific loss through this radiative process is

$$\left(\frac{dE}{dx}\right)_{rad} = -\frac{NEZ(Z+1)e^2\alpha}{m_0^2c^4} \left(4\ln \frac{2E}{m_0c^2} - \frac{4}{3} \right) \quad (2.3)$$

This process becomes relevant at energies above a few ten's of MeV where its contribution is greater than the collision process [19].

Since the energy loss by braking-radiation depends strongly on the absorbing material, an important parameter is defined: the critical energy,

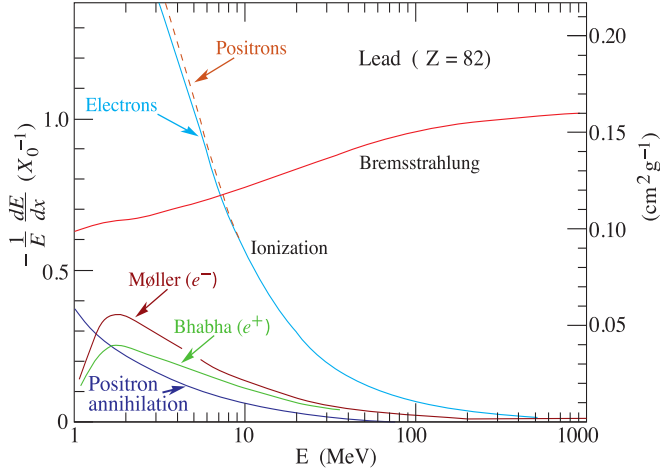


Figure 2.2.: Fractional energy loss per radiation length in lead as a function of the electron or positron energy [18].

E_c , where the probability of the radiation loss equals the probability of collision loss, defined by Eqs. 2.2 and 2.3. Fig.2.2 shows the contributions of both components for lead: the critical energy is around 7 MeV, and so former becomes dominant at lower energies and the latter at higher energies.

2.1.3. Energy deposited by photons

When a photon interacts with matter, the processes involved are dependent on the energy of the incident photon and on the atomic number (Z) of the material. The main interaction of X-rays and γ -rays with matter is basically due to the three processes that will be shortly described here (for a more detailed explanation, see, for instance, Refs. [2, 18, 19]):

- The photoelectric effect.
- The Compton scattering (including Rayleigh scattering).
- The pair production.

Photoelectric effect This effect is the more likely for photons of low energies and consists of the total energy transfer from the photon to an atomic electron, that is then ejected from the shell of the absorbing atom, and so the energy transferred to the outgoing electron is:

$$E_e = h\nu - \phi \quad (2.4)$$

where E_e is the energy of the ejected electron, $h\nu$ is the energy of the incident photon and ϕ is the binding energy of the electron. It is worth bearing in mind that the ejected electron can have energy enough to produce further excitations or ionisations, in a chained way.

Compton scattering The Compton scattering process is dominant at intermediate energies. The incident photon interacts elastically with an electron and the total energy and momenta are conserved after deflecting an angle θ . The energy of the deflected photon is dependent on such angle,

$$h\nu' = \frac{h\nu}{1 + \frac{h\nu}{m_0c^2}(1 - \cos\theta)} \quad (2.5)$$

The highest energy that can be deposited, corresponding to full back-scatter, is called the Compton edge. For low scattering angles, the energy transferred approaches to zero, meaning that the γ -ray is not detected in a single criterion. The outgoing electron can go through secondary interactions, and the deflected photon can, either escape or undergo a new photoelectric or Compton interaction.

Pair Production (PP) The pair production contribution starts when γ -ray energies are larger than the sum of the rest masses of the lightest leptons (e^- and e^+), being this energy threshold 1.022 MeV. Such process involves the presence of a nucleus in order to conserve momentum and so the angles of the created leptons partly depend on the energy of the initial γ -ray. Once again, it is worth mentioning that the lepton pair will produce further interactions in its track, being remarkable the case of the positron, that will end by annihilation with one electron of the medium, creating so two back-to-back photons of 511 keV that can newly interact at random.

2. Scintillator detectors

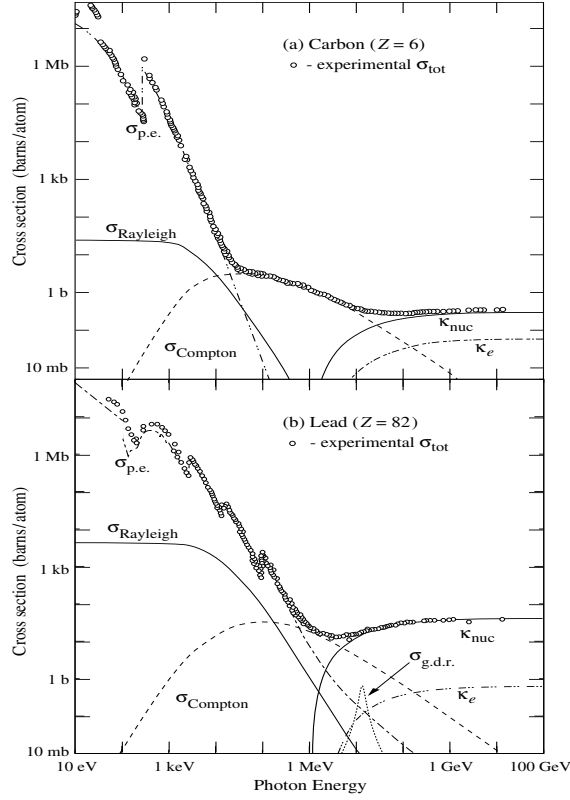


Figure 2.3.: Photon total cross sections as a function of incident photon energy in carbon and lead [18]:

$\sigma_{p.e.}$ = Atomic photoelectric effect

$\sigma_{Rayleigh}$ = Rayleigh (coherent) scattering-atom neither ionised or excited

$\sigma_{Compton}$ = Incoherent scattering (Compton scattering off an electron)

κ_{nuc} = Pair production, nuclear field

κ_e = Pair production, electron field

$\sigma_{g.d.r.}$ = Photonuclear interactions, most notably the Giant Dipole Resonance. In these interactions, the target nucleus is broken up.

Original figures through the courtesy of John H. Hubbell (NIST).

In Fig. 2.3 is shown the total interaction cross section for two different materials as a function of the energy of the incident photon. The figures show the difference on the contribution of such processes being remarkable the higher contribution of the pair production in the lead case, because of its higher Z .

2.2. Scintillation detectors

A generic scintillation detector is made of a scintillator optically coupled to a photodetector, and can be simply seen as a transducer of the ionisation radiation or charged particle crossing its active volume, into an electronic pulse able to be handled by the corresponding front end electronics.

The scintillation mechanism

The energy deposited by the impinging ionising particle or photon will be followed by the emission of photons in the visible or near the visible energy range. This effect requires a further explanation based on the use of the energy-levels model of a crystal.

An inorganic scintillator crystal has a valence band, where all the energy levels are occupied by electrons and a conduction band that are ideally empty and separated a distance in energy called bandgap. When ionisation radiation hits the material, it creates a number of electron-holes pairs proportional to their incident energy. In Fig. 2.4, where a simplified process of scintillation is sketched, one can see the creation of an electron-hole pair by the interaction of a photon with an electron that occupied a energy level of the valence band. The electron is promoted to the conduction band and then captured by the highest energy levels of the dopant material and, correspondingly, the hole is captured by the lowest levels. The recombination of both in the luminescence centre results in the emission of a photon. See Refs. [1, 20] for deeper information about the scintillation process.

Most of inorganic scintillator crystals are impurity-activated, what means that the final light produced in the scintillation process is due to the pres-

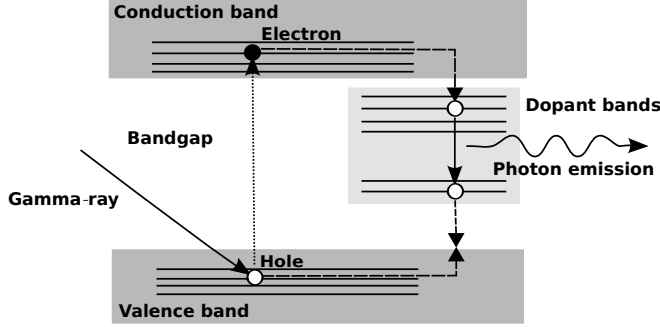


Figure 2.4.: Schematic representation of the electron structure in a scintillation material with a dopant, that plays a role as luminescence centre. The scintillation process is also shown. Other processes involved are neglected for the sake of simplicity.

ence of a small concentration of specific impurities (dopants), here called luminescence centres. In non-doped crystals, the scintillation process can still be present due to the fact of a stoichiometric excess of one of the constituents of the crystal occupying interstitial positions in the crystal lattice and so working as a luminescence centres. Such materials are called self-activated. The presence of such luminescence centres creates additional and localised energy levels, narrower than the energy bandgap of the crystals, that bandgap must be larger than around 3 eV, the typical energy of visible and UV photons, in order to the material be transparent to the visible light.

The electron-hole pair creation needs a minimum energy equals to the band-gap energy E_g . The number of pairs created by an incident γ -ray is given by

$$N_{e-h} = \frac{E_\gamma}{b E_g} \quad (2.6)$$

where the parameter b has a value that depends on the nature of the host matrix. For the crystals studied in this work, $b \approx 2$. Following this model, the maximum number of photons created by an incident γ -ray or charged particle should not exceed the number of pairs; as from Eq. 2.6, i.e., this maximum is one tenth the energy of the impinging photon, roughly

speaking. This value is typically provided in units of photons/MeV, being known as intrinsic light yield [10], because the actual L.Y., (what it is in fact achieved) is lower due to self-absorption and the energy lost in different mechanisms, as the creation of phonons, among others.

Taking into account the timing of these processes, the time profile of the light glint should have a very fast leading edge (the time spent in the excitation of the luminiscence centres), typically followed by a simple exponential decay (corresponding to the mean life. τ , of the excited states) given by:

$$L(t) = L_0 e^{-t/\tau} \quad (2.7)$$

This simple model is a rough approximation, appropriate for many scintillator materials, however, more contributions to the exponential decay are appreciated, including long lived luminiscence. Some crystals can have two or more kind of luminiscence centres, with different time constants, [19] leading to a more realistic timing behaviour given by:

$$L(t) = \sum_{i=1}^n \frac{A_i}{\tau_i} e^{-t/\tau_i} \quad (2.8)$$

where τ_i is the decay constant for each component and A_i is the proportional weight of each one of the n components [21].

For a scintillation detector (composed of the scintillator and the optodevice coupled to them), the capability of the scintillation light to quickly be collected by the optodevice is an important aspect for the preservation of the light yield and, therefore, of the energy resolution. As the light produced at the luminiscence centres is isotropic, several reflections in the wrapping reflector are expected. Moreover, real crystals are always characterized by the presence of some impurities that may also absorb photons. As a consequence, the size, shape and finishing of the scintillator crystals determine its properties, as the longer the distance a photon has to travel inside them, the higher is the probability to be lost. In Ref [22] is shown how, for very fast crystals, as CeBr_3 and $\text{LaBr}_3\text{:Ce}$, the size affects not only the energy resolution but also the apparent scintillation decay time.

Photodetectors

The light flashes produced within the scintillator crystals require fast photodetectors with the highest quantum efficiency (Q.E.), in order to detect the reduced number of visible photons produced during the scintillation process. Moreover, the scintillator L.Y. is distributed along a certain wavelength spectrum, matching more or less the spectral sensitivity of the photodetector, that has a Q.E. depending also on the wavelength. The convolution of the L.Y. function with the Q.E. one, will give the overall spectral efficiency of the detector. Furthermore, the appropriated optical coupling plays a very important role, as well as the matching between the size of the exit window of the crystal and the active area of the photodetector.

2.3. Scintillator detectors used in this work

In the last decades more and more new types of inorganic scintillator crystals have been developed, enhancing properties of traditional scintillators, where the former reference was NaI(Tl). Used widely in both nuclear and high-energy physics, as well as for medical applications and industrial systems, the improvement of their properties such as light yield, energy resolution, detection efficiency, pulse linearity or time resolution is a continuous challenge. When growing those crystals, where dopant materials are normally included, both the density of dislocations and the uniformity of the dopant distribution, influence the luminescence properties of scintillators.

In this work, four halide crystals have been characterised: three scintillators based on the Ce^{3+} ion (CeBr_3 and CeF_3) and a $\text{CsI}(\text{Na})$. The main properties of these scintillator crystals can be found in Table 2.1, where the NaI(Tl) scintillator is also included as a reference, and their dimensions are listed in Table 2.2. It can be seen that the best balanced crystal is CeBr_3 , having a fast decay and the highest L.Y., besides an emission peak matching well the Bialkali photocathodes sensitivity. The CeF_3 crystal has the fastest decay constant besides the higher density and effective atomic number, with the drawback of the poorer L.Y., by a factor of ten, being so competitive only at energies well above 1 MeV. The $\text{CsI}(\text{Na})$ crystal is

not the better but it is the cheaper and does not behaves so bad, as will be explained along the next Chapters.

Scintillator crystal	CsI(Na)	CeBr ₃	CeF ₃	NaI(Tl)
Density (g/cm ³)	4.51	5.20	6.16	3.67
Decay constant, τ (ns)	630	18-20	3,27	250
Emission peak, λ (nm)	420	380	300,340	415
L.Y. (ph/keV)	35-42	45-60	0.2,4.3	38
Refractive index, n	1.84	2.09	1.62	1.85
Crystal structure	Cubic	Hexagonal	Hexagonal	FCC
Effective atomic number, Z_{eff}	54	45.9	53	50
Hygroscopicity	Yes	Yes	No	Yes

Table 2.1.: Main characteristics of scintillator crystals: CeBr₃, CsI(Na) and CeF₃ and NaI(Tl) [21, 22, 23].

Scintillator crystal	CeBr ₃	CsI(Na)	CeF ₃ _L50	CeF ₃ _L40
Dimensions(mm ³)	18x18x25	18x18x25	18x18x50	18x18x40
Finishing	Polished	Polished	Non-polished	Polished
Encapsulation by	Scionix	USC	USC	USC
Manufacturer	Scionix	MolTech	MolTech	MolTech

Table 2.2.: Main characteristics of the scintillator crystals used in this work.

2.3.1. Wrapping and encapsulation

In order to collect as much light produced by the ionising particles or γ -rays, the crystals are wrapped by reflective materials that have been proved to be more efficient when they are dispersive. Both the election of wrapping materials, as well as a good tight coverage, are crucial when looking for the best efficiency in the scintillation light collection that redounds to the higher energy resolution. The most common used wrapping material is PTFE (Teflon) because of its high light diffusion and its easy use; the ever most efficient material is Enhanced Specular Reflector (ESR) from 3M, [24]) whose reflectance is higher than 98% (see Ref. [25] for a comparative study).

2. Scintillator detectors

The hygroscopicity of the materials can degrade the properties of the crystals, affecting their transparency, (the so-called *yellowing*) and worsening the transmission of the light created in the scintillation process. Therefore, an appropriated encapsulation must be made in cases of high hygroscopicity to avoid the absorption of moisture from the environment.

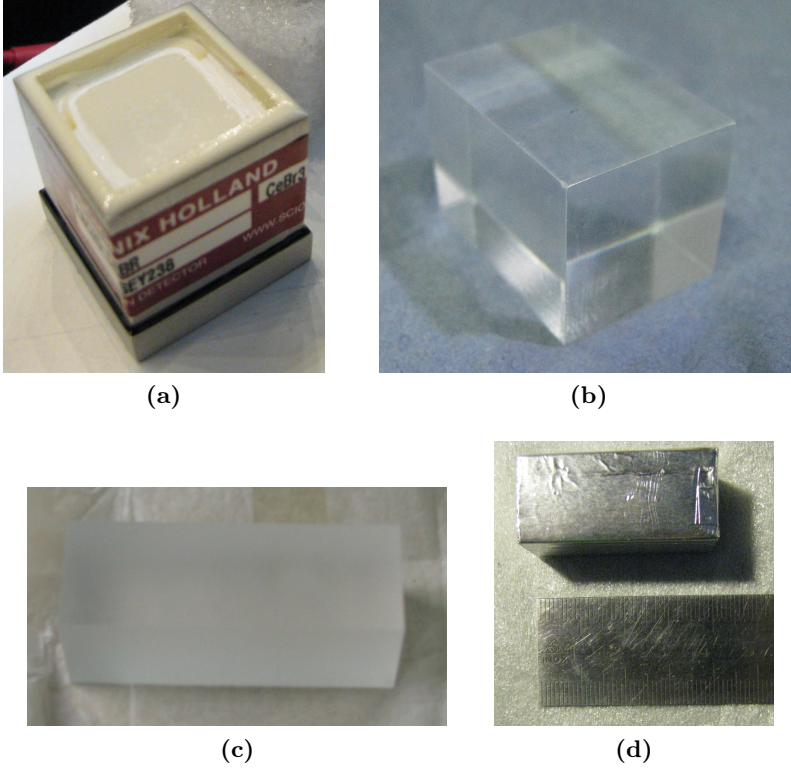


Figure 2.5.: Scintillator crystals used in this work: (a) CeBr_3 crystal encapsulated by Scionix. (b) $\text{CsI}(\text{Na})$ crystal. (c) CeF_3 crystal $L = 50$ mm. Note the non-polished surface. (d) CeF_3 crystal $L = 40$ mm wrapped by two foils of ESR from 3M reflector material.

CeBr_3 CeBr_3 crystal is highly hygroscopic and, therefore, the encapsulation was made by the manufacturer. The crystal was surrounded by a 0.5 mm of Teflon reflector, and a quartz window ($n_{\text{quartz}} = 1.54$) was placed

over the exit window of the crystal. The assembly was then encapsulated in an aluminium housing with 1.5 mm thick walls.

CsI(Na) CsI(Na) crystal is less hygroscopic than CeBr₃, and so, the encapsulation could be made by us in our USC laboratory. The wrapping of the crystal consisted of two foils of ESR. Black adhesive tape was wrapped around plus two 2 mm sheets of G-10, in order to tight the crystal to the walls of the aluminium housing (30mm x 30mm x 30mm). The input crystal face was sealed using an aluminium adhesive tape of 0.75 mm thickness from 3M.

CeF₃_L50 This crystal is non-hygroscopic. Similarly to CsI(Na), the CeF₃_L50 crystal wrapping consisted of two foils of ESR and black adhesive tape, plus two sheets of G-10 in an aluminium package of 25 mm x 25 mm x 50 mm.

CeF₃_L40 CeF₃_L40 was simply wrapped using two foils of ESR without aluminium housing. Depending on the sort of measurements, two wrapping configuration were performed:

- A: having an opening of 2 mm in the input surface to let the α particles interact with the crystal.
- B: a whole wrapping of two foils of ESR.

2.3.2. Photodetectors used

Photodetectors can be classified mainly in two groups: Photomultiplier Tubes (PMT) and Si-based photodetectors, such as PIN Diode (PD), Avalanche PhotoDiode (APD) and Silicon PM (SiPM).

The photomultiplier tubes and PIN diode photodetectors used in this work, will be briefly described in the following. For SiPMs see Ref. [26] and references therein.

R7600U-200 Photomultiplier Tube The advances on PMTs in 90s decade had led to improvements in their design and development. An step forward was done by Hamamatsu at the R&D for the Super-Kamiokande experiment, boosting the technology applied to them. For instance, the noise level was reduced by interposition of insulator materials between the adjacent dynodes, preventing ions and light feeding-back to the photocathode in the electron multiplication process. The positions of the first and second dynodes were optimised for a good efficiency collection. In order to focus photoelectrons by electron-lens effect, more efficiently guiding photoelectrons from the photocathode to the first dynode, a new technology to arrange grid pattern between the photocathode and immediately in front of the first dynode was developed.

The PMT R7600U-200 manufactured by Hamamatsu, besides the properties above mentioned, has also improved the feedback prevention by using metal packages (technology developed in 1992). In addition, a novel technology for optimising the position between the first and second dynodes has been used; this technology was invented for metal channel dynodes with no grid patterns (see Fig. 2.6) [27]. As a result of this inheritance, Hamamatsu developed the smallest TO-8 metal package photomultiplier tubes. The cubic shape of such PMT facilitates stacking the photodetectors, when a big detector requires large segmentation [28].

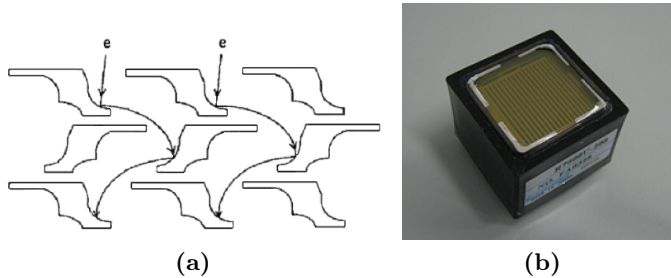


Figure 2.6.: Cross section of metal channel dynodes [27] (a). PMT mod. R7600U-200 from Hamamatsu (b).

The PMT R7600U-200 also offers a very high photocathode quantum efficiency, 43 % at 400 nm, called "ultra bialkali" (UBA). Former high sensitivity photocathodes, called "superbialkali" (SBA), deliver a lower

quantum efficiency of 35% at 350 nm. Fig. 2.7 shows typical spectral response curves of the UBA, SBA and BA photocathodes.

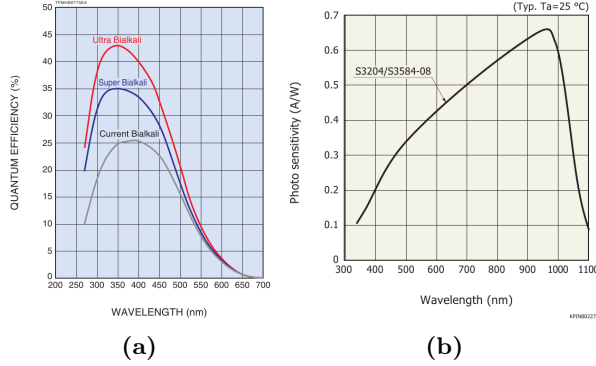


Figure 2.7.: Q.E. of UBA, SBA and BA photocathodes (a). Spectral response of PIN diode model S32004-08 (b). Both courtesy of Hamamatsu Photonics K.K.

Just to see the evolution of the photocathode efficiency, let us mention that the Q.E. of the first PMT, built in 1930, was less than 1 % at peak wavelength and then, the research and development of the photocathode materials got improved the Q.E. up to 25% in the mid-1960s. These increments of the Q.E. become very relevant for those applications and experiments where the number of photons emitted by the photon source (scintillator crystal) is scarce [29].

2.3.2.1. Bias voltage curve

Hamamatsu Photonics claims an exponential relation of gain versus the voltage supply (see Fig.2.8) for the PMT R7600U-200 using the standard VD circuit (see Ref. [9]). The characterisation of the newly designed VD circuit, requires a new calibration and two measurement methods have been carried out for this purpose.

The first method consists of the connection of the detector output signal directly to a YOKOGAWA oscilloscope [30]. For every value of a set of supplied voltages, a large amount of pulses were acquired when the

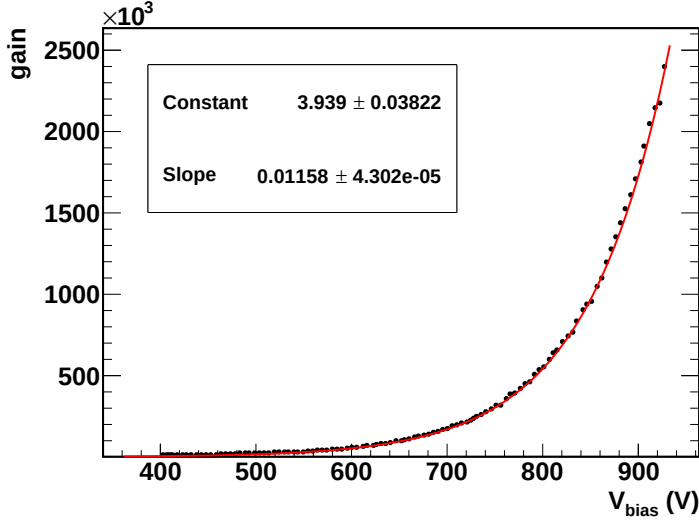


Figure 2.8.: Nominal gain as a function of the Voltage Supply of the PMT R7600U-200+E5996 socket. Courtesy of Hamamatsu Photonics K.K.

CeBr₃-PMT was irradiated by the ¹³⁷Cs radioactive source. Clearly, the signal size is proportional to the photoelectrons produced in the PMT cathode as well as to final multiplication in the dynodes chain. Then, every pulse was analysed using a digital algorithm (which will be explained in detailed in Chapter 2). The variation of the amplitude as a function of the supplied voltage for the CeBr₃-PMT can be seen in Fig. 2.9 (a), showing an exponential dependence as in Fig. 2.8.

The second method was based on the analysis of the centroid of the photopeak of 662 keV γ -rays from ¹³⁷Cs radioactive source acquired (which is also directly proportional to the gain) using a spectroscopic chain (explained in detail in the next section) at different supplied voltage. The measurement chain consisted of several active stages: an electronic preamplifier, an spectroscopic amplifier mod. 2022 manufactured by CAN-BERRA and a MCA from AmpTek. The correlation between the centroid of the photopeak and the supplied voltage supplied confirms the exponential dependence, as shown Fig. 2.9 (b).

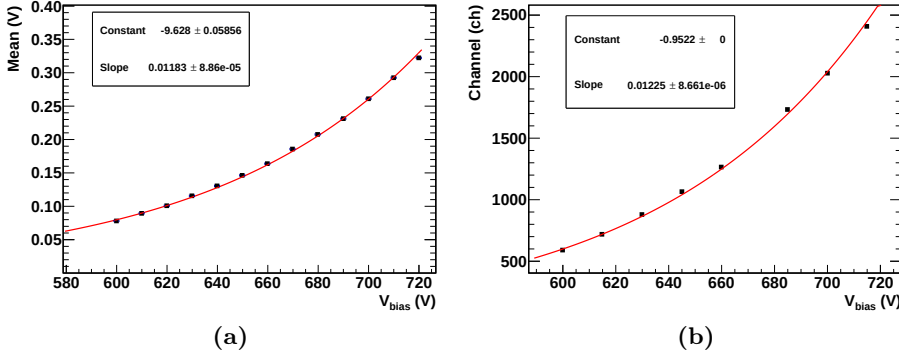


Figure 2.9.: Maximum pulse amplitude as a function of the supplied voltage of the PMT R7600U-200+USC-VD, measured with a YOKOGAWA oscilloscope (a). Centroid for 662 keV γ -rays from a ^{137}Cs a function of the supplied voltage measured with a spectroscopic chain (b).

PIN Diode S3204-08 The PIN diode was one of the first developed silicon, Si, photodetectors. Its inner structure roughly consists of the junction of three silicon layers (in order): a Si layer heavily doped with donors (n+ region), a Si intrinsic piece and a Si layer heavily doped with acceptors (p+ region). This configuration is reverse-biased, forming a depleted region that contains the whole intrinsic piece and extending to both the p+ and n+ regions, forming a wide light detection area (see Fig. 2.10 (a)). PIN diodes are usually covered by a thin layer of highly transparent resin for an optimal coupling as well as preventing a possible mechanical damage of the first doped silicon layer. Solid-state devices are advantageous over PMTs when operating in the presence of a magnetic field, that disturbs the swarm of electrons created in the PMTs stages and does not in the PIN diode case [31]. As a drawback the Q.E. of the PIN diode decreases at the wavelengths of our interest, being so its overall efficiency much lower than in the PMT R7600U-200. The spectral response for PIN diode S3204-08 is shown in Fig. 2.7 (b).

The PIN diode, model S3204-08 from Hamamatsu, has a large active area with a compact design, as can be seen in Fig. 2.10 (b); and its power

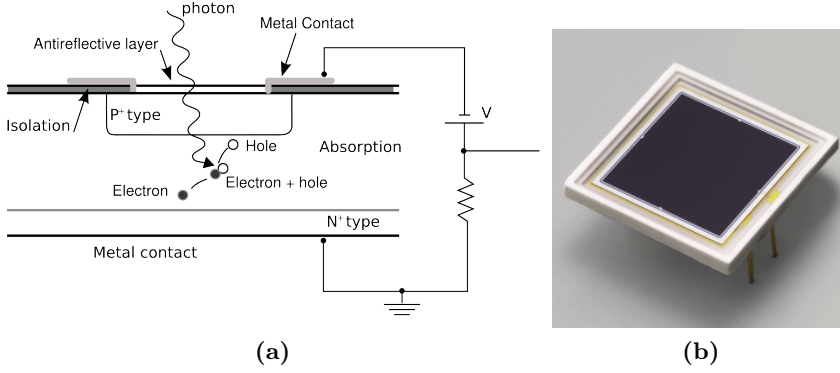


Figure 2.10.: Structure of a PIN diode, (a) [31]. PIN Diode S3204-08 from Hamamatsu (b). Courtesy of Hamamatsu Photonics K. K. [32]

supply voltage for a gain of $\times 10$ is around 70 V, as specified in Table 2.3.

	PMT R7600U-200	PIN diode
Bias Voltage(V)	-800	70
Gain	10^7	10

Table 2.3.: Photodetectors biasing.

2.3.3. Coupling scintillators to photodetectors

The four crystals were coupled to two different photodetectors attending to their output window and their emission spectra. Both the L.Y. of a scintillator crystal and the Q.E. of the photodetectors, are wavelength dependent (see Fig 2.7 (a)). The result of the convolution of both curves, called Photoelectron Yield, P.Y., is calculated and plotted in Fig. 2.11 for the three crystals, CeBr_3 , CeF_3 and $\text{CsI}(\text{Na})$ coupled to a PMT R7600U-200. Note the high P.Y. for CeBr_3 , and the bad performance of CeF_3 which emission peaks are too UV shifted.

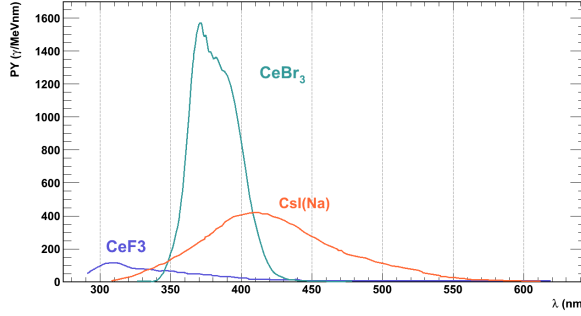


Figure 2.11.: Photon Yield of CeBr₃, CsI(Na) and CeF₃ [22, 33, 23].

Final assemblies

CeBr₃-PMT The R7600U-200 PMT and the CeBr₃ were coupled using two coupling materials: a Silicon Pad, mod. BC-634A, and optical grease, BC-630, both from Saint-Gobain Crystals [34]. The results obtained with the optical grease were comparable to those obtained when coupling with Silicon Pad. The set assembly will be called CeBr₃-PMT onwards.

CsI(Na)-PMT An aluminium piece was machined in order to a proper assembly between the crystal encapsulated and the surface of the R7600U-200 PMT. This piece was glued to the plastic coating of the PMT. A ESR mask surrounding the borosilicate window that is set in order to avoid light losses. The coupling is made using a bi-component adhesive Scionix RTV 681 from Scionix [35]. The set assembly will be called CsI(Na)-PMT onwards.

CeF₃_L40-PMT and CeF₃_L50-PMT Both crystals were coupled to the R7600U-200 using optical grease, BC-630 and an ESR mask as the described previously [34]. The assemblies will be called onwards CeF₃_L40-PMT and CeF₃_L50-PMT, respectively.

CsI(Na)-PIN The CsI(Na) crystal was glued to the PIN diode S3204-08 using Meltmount n = 1.582 adhesive [36]. The set assembly will be called

CsI(Na)-PIN onwards.

2.4. Simulation work

Simulations are essential to understand the response of detectors to different kind of particles in function of its kinetic energy. Therefore, the simulations performed for two different type of crystals are described here in order to better understand the response of the scintillator crystals, for both γ -rays and electrons. Finally the results and conclusions will be presented. The features of the simulation program here used, EnsarRoot [37], are described in the Appendix F.

2.4.1. Description of the simulation

Two punctual radiation sources -one for γ -rays, one for electrons, e^- - have been simulated. The sources were placed at 1 cm from the input window of the crystals. Their emission angles are $0^\circ \leq \theta \leq 15^\circ$ and $0^\circ \leq \varphi \leq 360^\circ$. The simulation medium is vacuum. The software provides an output ROOT file with different observables. The most relevant parameters for this study are the deposited energy in the crystals for different incoming energies in order to find out the detection efficiency of the crystals for a certain energy of the γ -rays and the most probable value of the deposited energy in the electrons case.

This simulation work has been performed for both CeBr₃ and CsI(Na) scintillators, with dimensions close to the ones having the real detectors used in the rest of the Thesis work. For the sake of simplicity, the material simulated was CsI for the CsI(Na) crystal. The aim of the simulation performed in this work is to determine the energy deposited in each crystal and, therefore, the dopant, (Na in this particular case) does not alter significantly the characteristics of the CsI. The characteristics not affected by the dopant are the density of the material and its radiation length. See Table 10.9 in Ref. [38]. Nevertheless, the optical characteristics, such as wavelength emission or refractive index were significantly modified.

Three different configurations were defined for each crystal as follows:

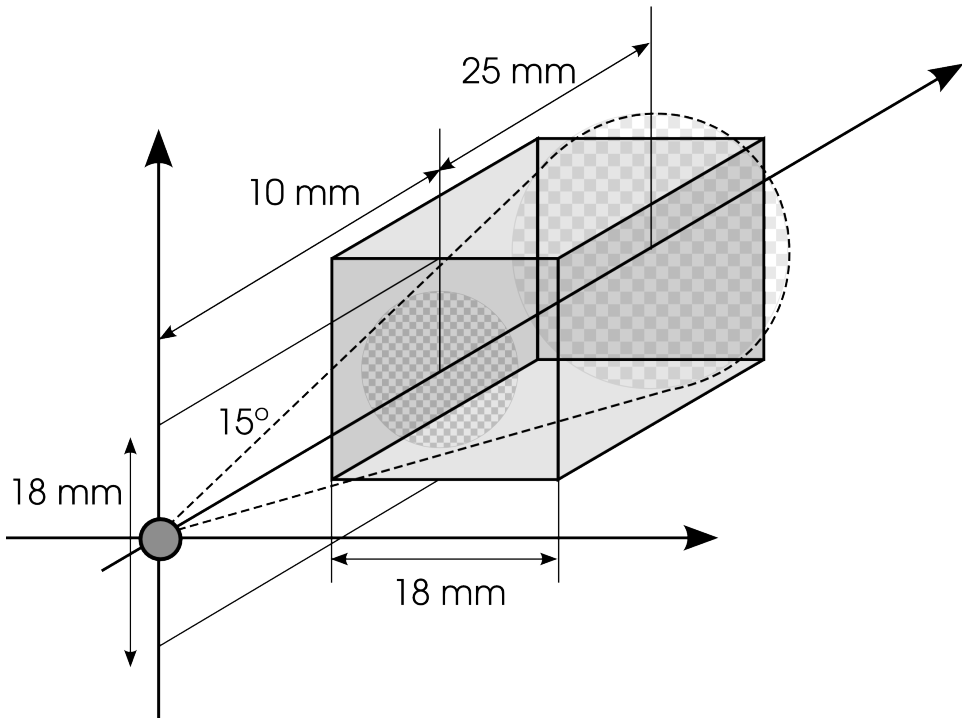


Figure 2.12.: Schematic set-up for simulations. The simulated source is sketched by the circle placed at the origin of coordinates. The parallelepiped crystal is shown as well in the figure. The dash-line represents the solid angle from the source to the end of the crystal.

- a) Bare crystals. Dimensions (close to the real ones): $18 \times 18 \times 25 \text{ mm}^3$.
- b) Crystals in contact with an Al foil. 1.5 mm thick and an area of $18 \times 18 \text{ mm}^2$.
- c) The same as in the configuration c) but with a foil thickness of 5 mm.

The simulation results leads to the spectrum of deposited energy in the crystal as well as to an estimation of the counting efficiency. In order to get more realistic results an experimental smearing is included for each crystal, corresponding to the global detector resolution at 1 MeV. The energy threshold for the analysis of the results obtained through the simulations was 20 keV.

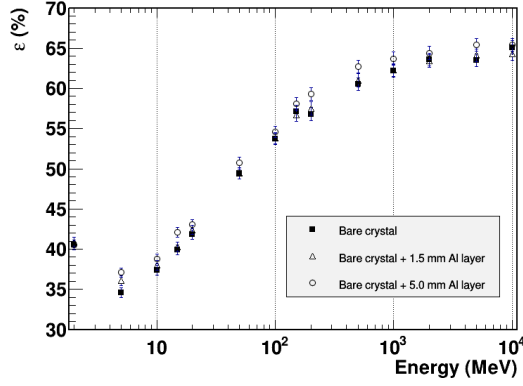
2.4.2. γ -ray simulations

The photon simulation consists of the emission of monochromatic γ -rays in a wide range of initial energies: from a few MeV to GeV. The simulation output provides a ROOT Tree that contains a set of observables, stored in a event-by-event basis. The observable of interest for the γ -ray simulation is the deposited energy by every incident γ -ray recovered from the Tree, using a script in ROOT. The same range of incident energies is simulated for the three configurations, stated above, of both crystals. The simulations were performed over 15000 events (15000 incident γ -rays).

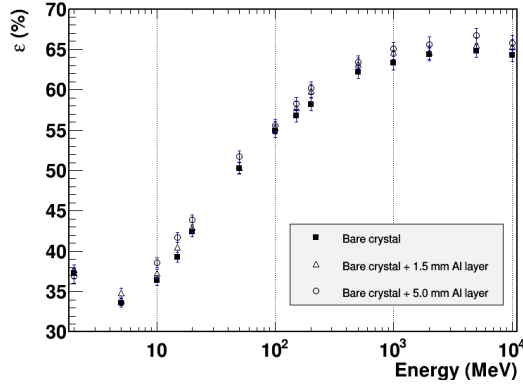
A study of the detection efficiency of the CeBr_3 and CsI was made. The detection efficiency relates the ratio of number of events registered by the crystal having an amplitude above a threshold well above a typical $\text{SNR} > 1$, over the events impinging on the crystal. In Fig. 2.13, (a) and (b), the respective values of such efficiencies for each incident energy and each configuration are shown. It is observed that the detection efficiencies rising up to 60% from a few MeV to GeV, where the efficiency saturates, because (see the spectra in Appendix G) the most probably deposited energy in these crystals never exceeds 20 MeV.

A similar behaviour is observed in the case of the CsI crystal, although the efficiency values are slightly below than the ones in the CeBr_3 for low energies and slightly above at high energies.

It is worth pointing out that at low energies, the photopeak efficiency,



(a)



(b)

Figure 2.13.: Detection efficiency of CeBr₃ (a) and CsI (b). The three simulation configurations are shown in both cases.

(the efficiency of the crystal when the the full-energy of the incident particle is registered by the crystal), decreases as the incident energy increases, (see Figs. 2.14 and 2.17) as it was observed in γ -rays radioactive sources spectra experimentally acquired in Chapter 3. It is clear that the size of the crystal plays an important role when dealing with the photopeak efficiency: larger crystals have higher photopeak efficiency because less energy escapes from the crystal. In this particular case, the crystals can

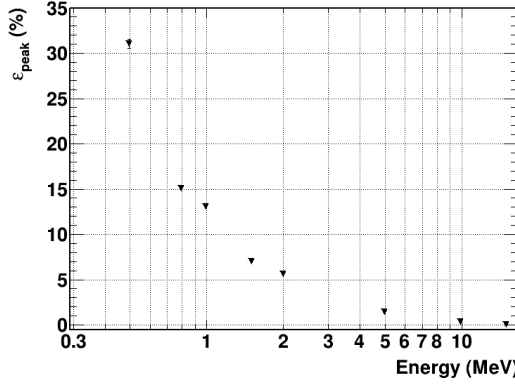


Figure 2.14.: Photopeak efficiency for bare CeBr₃ crystal.

be classified as small detectors in agreement with the mean free path of the γ -rays in the material [19]. From Fig. 2.13 it becomes clear how for 2 MeV the photopeak and Compton energies are the most probable, whereas at 5-10 MeV the escaping peaks becomes very relevant. As a conclusion, both crystals behaves very similarly and the effect of having aluminium sheets (the three configurations here simulated) is not so relevant, showing similar counting efficiencies all along the energy range of interest.

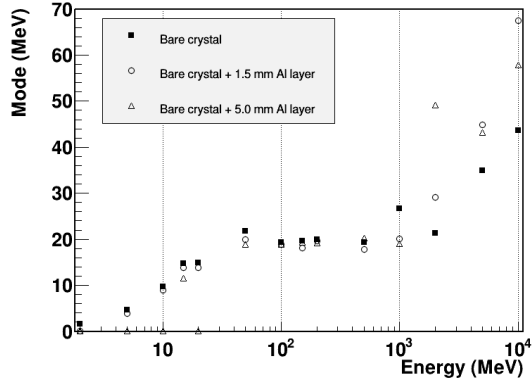
2.4.3. Electron simulations

A similar simulation was performed for electrons. The crystals size and the simulation configurations were as in the previous Subsection. Monochromatic electron sources were used as event generator and the range of incident energies spans from 2 MeV to 10 GeV and in Fig 2.18 are the simulated energy spectra of electrons in the CeBr₃ crystal. It can be seen the difference with respect to those created by γ -rays as in this case the energy deposition mechanism is simpler. Nevertheless, above 5 MeV the Bremsstrahlung effect opens the way to photons escaping from the active volume. Once again, for the higher energies is worth distinguishing between the most probable energy deposition in these so small crystals is around 20 MeV. The most probable value of the deposited energy in the crystal, onwards **mode**, and the mean value of the deposited energy,

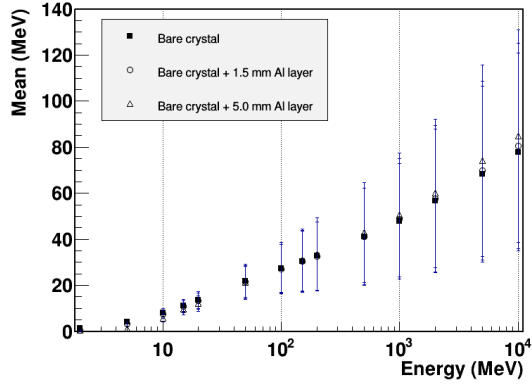
onwards **mean**. A comparison between both observables provides information about the distribution of the deposited energy for each incident energy in Fig. 2.15.

For both crystals, the mode and the mean value increase in parallel until around 50 MeV, getting values up to around 20 MeV where the mode rising stalls whereas the mean value continues to grow, even though its uncertainty increases dramatically. It is worth to note how the mode rise again above 1 GeV, even though its uncertainty starts to increase too. It is notable that of the energy region where the mean and mode values begin to differ is well above the critical energy of both crystals, being 11.7 MeV in CsI and 17.5 MeV in CeBr₃ [39], that implies that above such region, the Bremsstrahlung emission being predominant, starts to significantly escape from the active volume.

In Figs. 2.15 and 2.16 is shown how at the lower energies, for the third configuration, the electrons barely deposit energy in the crystals due to the fact that the 5 mm thick aluminium foil attenuates the least energetic electrons, preventing so their detection in the crystals. In the range from 50 to 1000 MeV the mode gets a plateau and from that energy on the mode is increasing again.

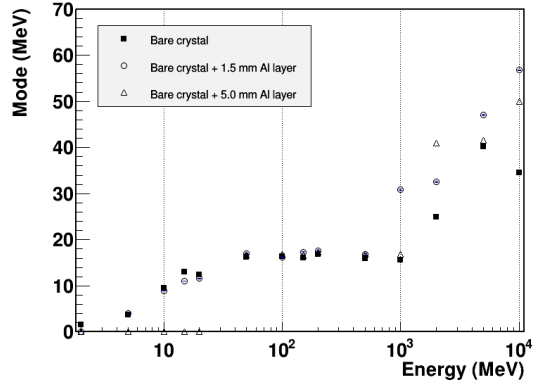


(a)

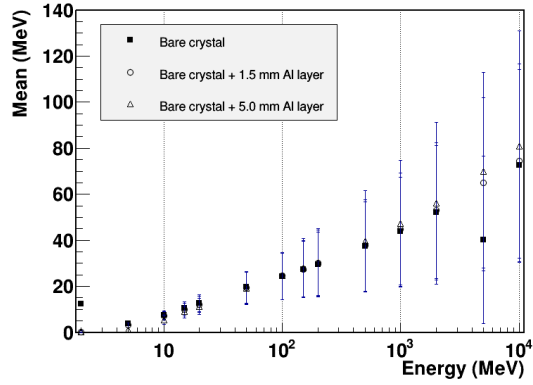


(b)

Figure 2.15.: Mode value (a) and mean value (b) for CeBr_3 . The three simulation configurations are shown.



(a)



(b)

Figure 2.16.: Mode value (a) and mean value (b) for CsI. The three simulation configurations are shown.

2. Scintillator detectors

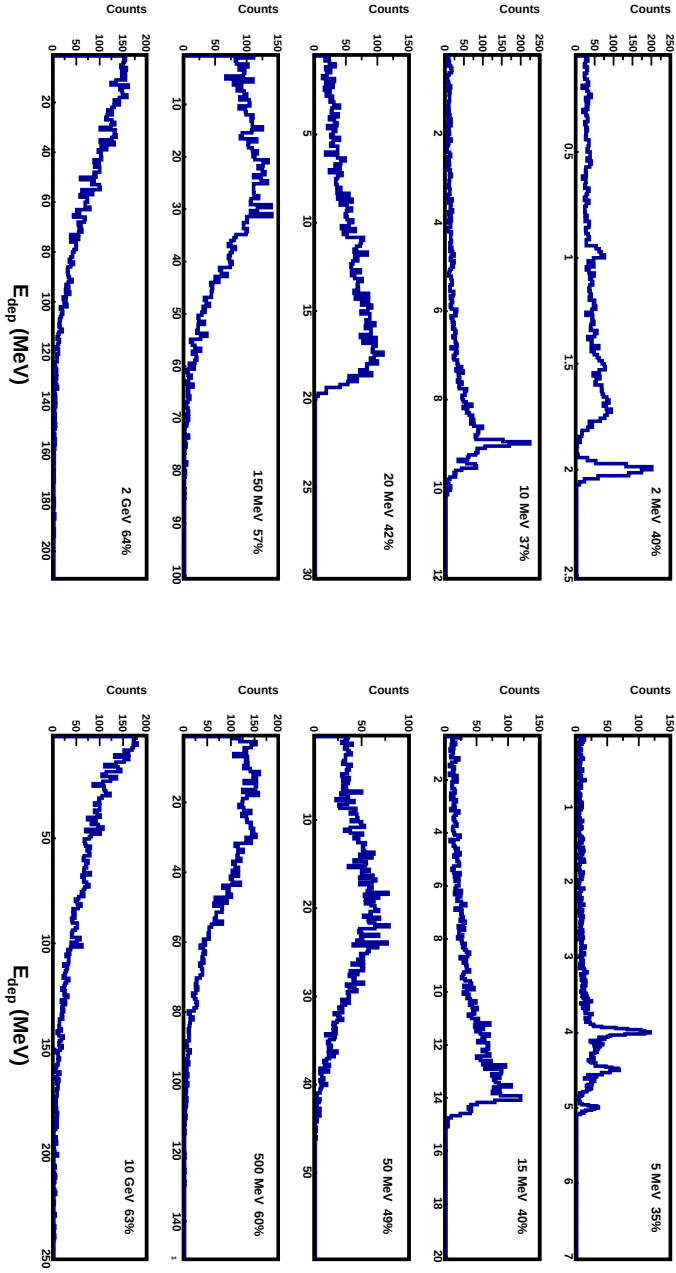


Figure 2.17: CeBr₃ bare crystal. Energy deposited spectra at different initial energy for γ -rays. The counting efficiencies are shown for each energy.

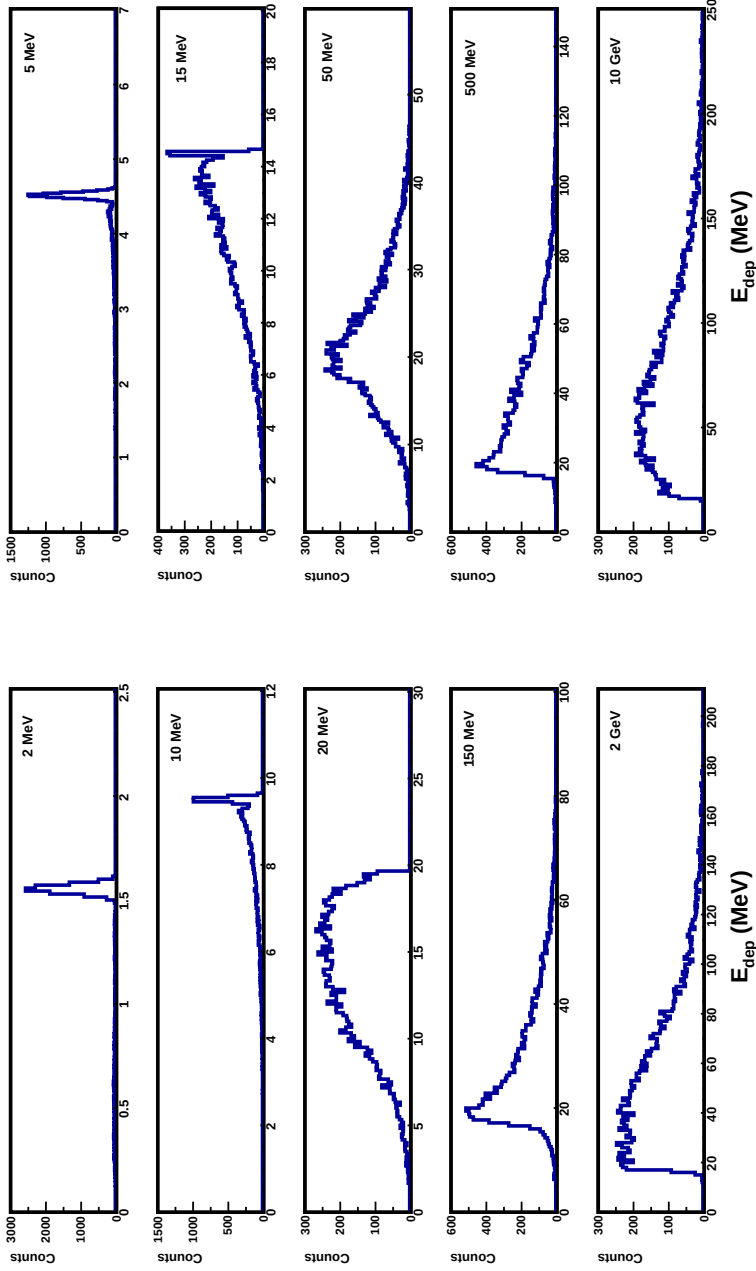


Figure 2.18.: CeBr_3 bare crystal. Energy deposited spectra at different initial energy for electrons.

2.5. Conclusions to the Chapter 2

After reviewing the mechanisms of creating a certain light yield in scintillation crystals and the way this light is converted to an electronic pulse by the corresponding optodevice, are presented the simulation work done to better explain the results gotten both in lab bench tests and in the CERN-n_TOF experimental facility. The simulations performed using the EnsarRoot simulation program for CeBr₃ and CsI crystals have the clues to interpret the behaviour of both crystal for γ -rays and β particles. It is worth mentioning that the high detection efficiency for γ -rays, greater than 40 % in the energy range studied and increasing up to 60 % at energies larger than 100 MeV. An simulation for the deposited energy by β particles in both crystals provides accurate information about the threshold energy when radiation losses become relevant.

3. Test results with radioactive sources and cosmic-rays

In Chapter 1 the challenges of dealing with fast and high-L.Y. scintillator crystals are discussed, besides some technical solutions to face them. Those scintillator detectors studied in this work have been introduced as well. In this Chapter is shown how the application of such techniques permits a proper characterisation and a better performance of these fast radiation detectors. Tests with radioactive sources were performed in order to characterise the response to the deposited energy, so that the detectors linearity, energy resolution, time resolution and efficiency will be discussed, as well as its ability to identify the impinging particle kind.

3.1. Detectors calibration: spectra acquisition and linearity

The ^{152}Eu , ^{137}Cs , ^{60}Co and ^{88}Y radioactive sources used in the work described in the following sections are mainly γ emitters; a β emitter, ^{90}Sr , an α source, ^{238}Pu , and finally, one of Am-Be, giving both γ -rays and neutrons was used also. These radioactive sources allow the study of the detectors behaviour in a range of energies from 121 keV to more than 4.4 MeV.

3.1.1. Energy resolution and linearity

The typical set-up to measure the different spectra was described in Section 1.1.2 as well as the procedures being used in this Chapter. The low-noise high-stability HV power supply from ISEG, module NHQ 225M [40], was feeding the optodevices which signal output was sent to a preamplifier and

3. Test results with radioactive sources and cosmic-rays

shaping stage (either the *Stretcher* PCBs described in the Appendix D, or the MPR-1 module from Mesytec [41] in the case of CsI(Na)-PIN), then connected to a SA, CANBERRA mod. 2022, and, finally, the amplified and shaped signals were acquired by a Multi Channel Analyser MCA-8000A from AmpTek [6], that digitises and transfers the data to a PC where the client software was installed.

Concerning the tests performed with the CeBr₃-PMT and CsI(Na)-PMT detectors using the most energetic γ -rays sources, ⁸⁸Y and AmBe, as they were placed at the EAR1 in the CERN-n_TOF facility, the set-up differed slightly from the one used for the measurements performed at the USC laboratory: the *Stretcher* PCBs used at n_TOF were early versions of the final design and the SA employed was an ORTEC mod. 570, from the shelves in the n_TOF experimental facility.

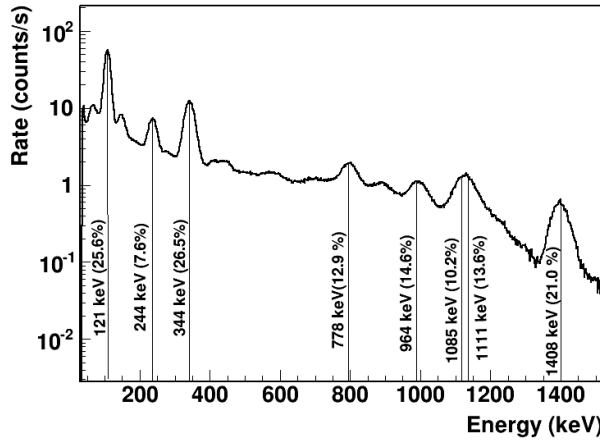


Figure 3.1.: The ¹⁵²Eu spectrum measured by the CeBr₃-PMT detector.

It is evident that for the channel-energy calibration of the detectors, the more values included, the more accurate the calibration will be. Therefore, ¹⁵²Eu source was used because it features eight peaks of relatively high intensities. Their energy (in keV) and relative intensities are, respectively: 121 (25.6%), 244 (7.6%), 344 (26.5%), 778 (12.9%), 964 (14.6%), 1085 (10.2%), 1111 (13.6%) and 1408 (21.0%).

Once calibrated the spectrum, the energy resolution capability of the detectors is characterised by the the width and the centroid of the measured photopeaks following the Eq.

$$R(E) = \frac{FWHM}{E} \quad (3.1)$$

as explained in Chapter 1. In order to obtain the measured energy resolution, each photopeak (see Fig.3.1) was fitted to a gaussian function plus a linear function [42] after subtracting the background radiation. The resolution was calculated from the centroid and sigma (σ) parameters given by the fit. It is worth saying that the two peaks at 1.086 and 1.112 MeV are only 26 keV apart from each other, what is around 2.4% of the peaks' energy and, therefore, they can not be resolved. Nevertheless, their relative intensities are quite similar and so, in this study, the apparent peak shape has been unfolded in two gaussian functions, getting in this way the resolution attainable at their middle point, 1.1 MeV.

CeBr₃-PMT

Test with γ emitters. Firstly, a test with γ -ray emitters was performed. The result of the energy-channel calibration of the CeBr₃-PMT, when used the *Strecher* PCB specifically design for this detector, can be seen in Fig. 3.2 (a) showing good linearity all along the energy range of the ¹⁵²Eu γ peaks. Related to the measured energy resolution, the results obtained were plotted as a function of the energy of the γ -rays, and then fitted to the two parameters equation

$$R(E) = \frac{p_0}{E^{p_1}}. \quad (3.2)$$

The energy resolutions given here, see Fig. 3.2 (b), are the result of the intrinsic resolution of the scintillating process in the detector, plus a series of contributions:

- the gaussian dispersion of the L.Y.
- the dispersion of the multiplication by the opto-device.
- the contribution from the electronic chain.

3. Test results with radioactive sources and cosmic-rays

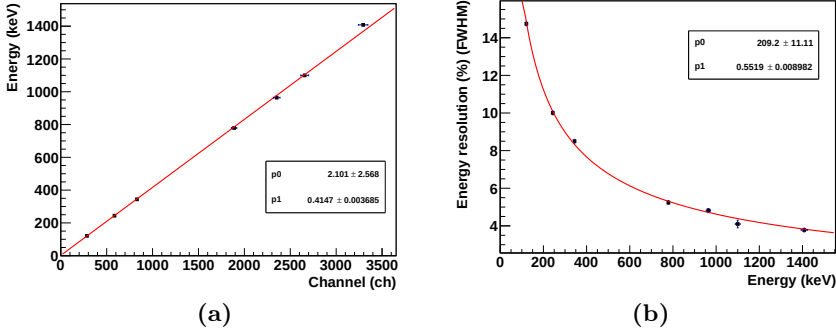


Figure 3.2.: CeBr₃-PMT linear energy calibration (a) and energy resolution as a function of the energy of the γ -rays from ^{152}Eu source (b)

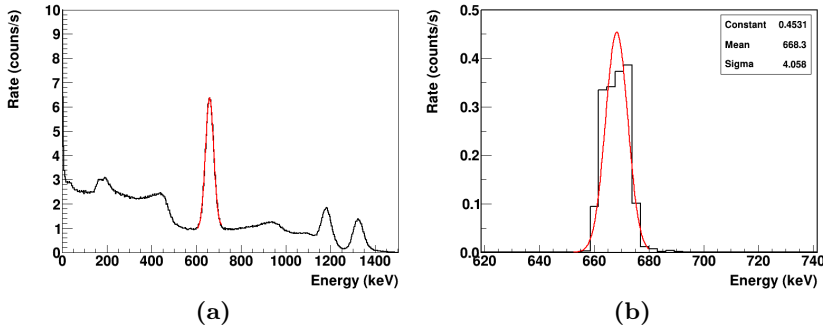


Figure 3.3.: $^{137}\text{Cs} + ^{60}\text{Co}$ energy spectrum using the CeBr₃-PMT detector (a). Gaussian fit to the contribution from the electronic chain to the energy resolution results (b).

In order to quantify this electronic chain contribution, the signal output from the CeBr₃-PMT was substituted, by an artificial pulse generator connected to the rest of the spectroscopic chain, including the *Stretcher* and the SA. The squared pulse from the signal generator was differentiated by means of a RC circuit. The amplitude of this signal was arranged to be similar to the signal produced by a γ -ray of 662 keV; The result seen in Fig. 3.3 (b), shows a sigma = 4 (FWHM = 9.4 keV), is leading to a $R_{\text{pulser}} = 1.4\%$. This dispersion includes the stability of the pulse

amplitude from the signal generator, that was calculated by means of a 5 GS/s digital oscilloscope to have a $\sigma/\text{amplitude} = 0.5\%$. Therefore, the resolution factor introduced by the electronic chain was $R_{elec} = 1.3\% \pm 0.2\%$ and the overall resolution was then unfolded by means of

$$R_{detector}^2 = R_{total}^2 - R_{elec}^2 \quad (3.3)$$

The results shown in Figs. 3.2 and 3.3 give a detector resolution of 5.6 % at 662 keV and 4.5 % at 1 MeV, with an energy relation very close to the square root of the energy.

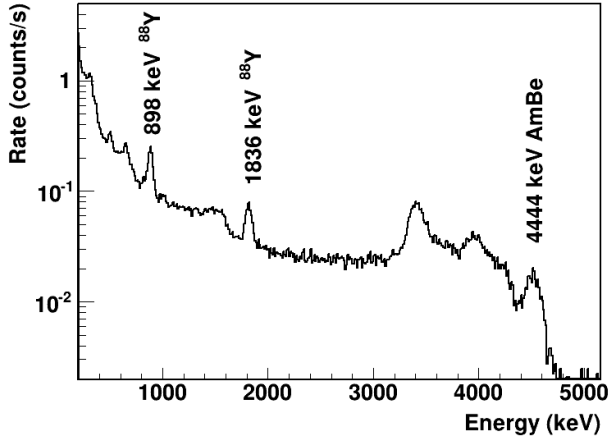


Figure 3.4.: ⁸⁸Y+AmBe spectrum acquired using CeBr₃-PMT detector.

As it was already mentioned, the ⁸⁸Y and AmBe spectrum was measured at the n_TOF facility, using a slightly different setup, proving the linear response of the detector to γ -rays of energy larger than 4.4 MeV. Fig. 3.4 shows the CeBr₃-PMT ability to detect 4.4 MeV γ -rays from the AmBe source, although its lower detection peak efficiency, in agreement with the simulations work described in Section 2.4 in the previous Chapter. This low photopeak efficiency is due to the high probability of secondary photons, either Compton or from electron-positron pairs, escaping by the crystal boundaries (see Section 2.1).

The intrinsic background has been measured in some published works

3. Test results with radioactive sources and cosmic-rays

on crystals of CeBr_3 , Refs. [43] [22], because the presence of contaminants that could disturb the measurement of γ -rays spectra. The background spectrum acquired in this work along 24 hours, see Fig. 3.5, does not show the presence of contaminants in the CeBr_3 scintillator crystal provided by Scionix.

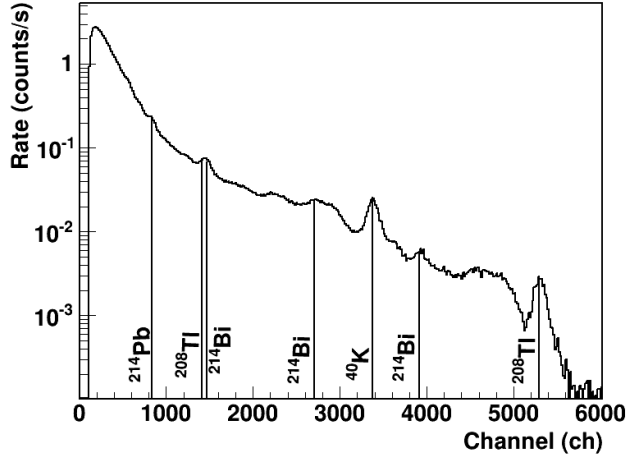


Figure 3.5.: Background radiation spectrum measured using CeBr_3 -PMT detector.

Test with a β emitter A ^{90}Sr source was used to determine the capability of the CeBr_3 -PMT to detect β particles. The measured spectrum is shown in Fig. 3.6. The simulation work carried out in Chapter 2 predicted the detection of β particles of such an energy by the CeBr_3 despite of an Al foil of 5 mm thickness. The performed test using ^{90}Sr confirms the simulation results: β particles were detected. Seeing in detail the spectrum acquired, two contributions of the continuous spectrum can be distinguished. One is coming from the emission of the β^- disintegration of ^{90}Sr whose endpoint energy is 546 keV. The other is coming from the β^- disintegration of the ^{90}Y , whose endpoint energy is 2284 keV, being thus energetic enough to pass through the 1.5 mm aluminium walls and to deposit energy in the crystal.

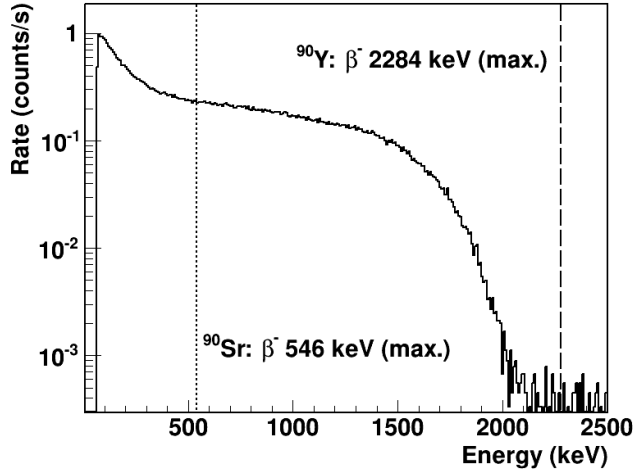


Figure 3.6.: ^{90}Sr spectrum. Note the two contribution of the disintegration at 546 keV and 2284 keV, after passing the Al wall.

CsI(Na)-PMT and CsI(Na)-PIN

The same procedure was followed for the CsI(Na)-PMT and CsI(Na)-PIN detectors when characterising them using γ -ray emitters sources. The energy-channel calibration as well as the energy resolution was measured using the ^{152}Eu radioactive source, and are shown in Fig.3.7 and 3.8. The CsI(Na)-PMT shows a linear behaviour in the ^{152}Eu measurements as well as in the ^{137}Cs and ^{60}Co spectrum (662, 1173 and 1332 keV photopeak energy, respectively), that can be seen in Fig.3.9 (a). As in the CeBr₃-PMT case, the CsI(Na)-PMT behaved properly when detecting γ -rays at higher energies, as shown in the spectrum from ^{88}Y and AmBe sources in Fig.3.10, where the observed low peak efficiency is in agreement with the results of the simulation work. The resolutions gotten from the 662 keV peak are 6.7% and 10.4%, respectively. The resolution dependence on energy is also very close to the root square of the energy.

The ^{137}Cs and ^{60}Co spectra measured by the CsI(Na)-PMT and CsI(Na)-PIN can be compared (see Figs. 3.9 (a) and (b)). Both detectors have a good linearity in the given energy range, but the photopeaks observed

3. Test results with radioactive sources and cosmic-rays

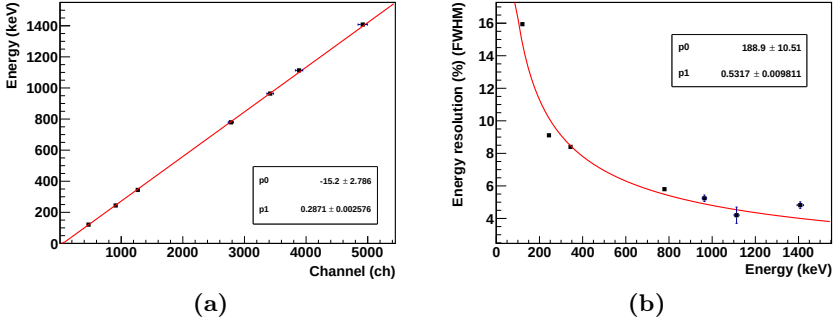


Figure 3.7.: CsI(Na)-PMT detector linear energy calibration (a) and energy resolution vs the energy of the γ -rays from ^{152}Eu source (b).

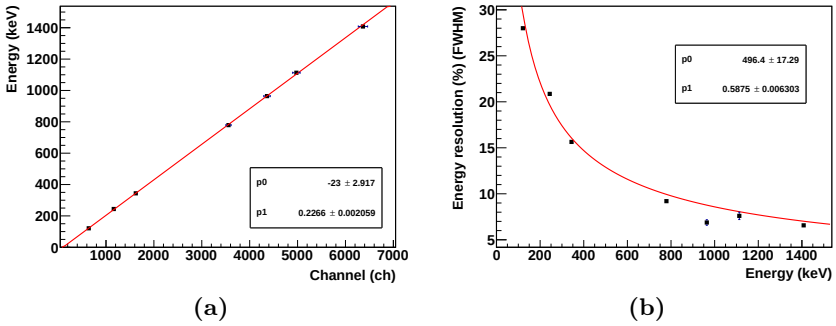


Figure 3.8.: CsI(Na)-PIN detector linear energy calibration (a) and energy resolution vs the energy of the γ -rays from ^{152}Eu source (b).

in the CsI(Na)-PIN spectrum are broader than the CsI(Na)-PMT ones, meaning a poorer energy resolution.

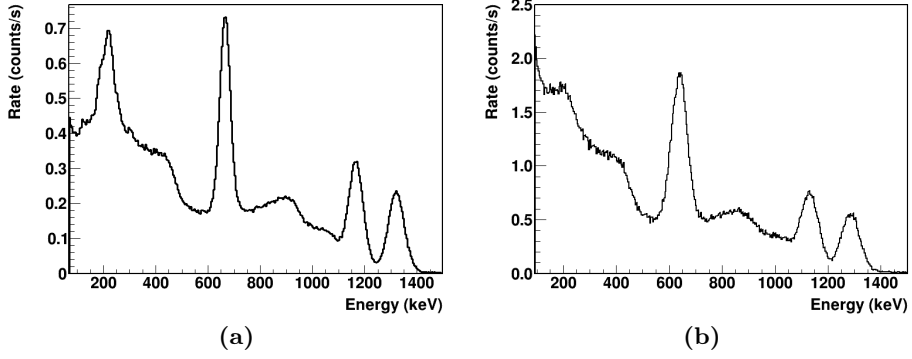


Figure 3.9.: $^{137}\text{Cs}+^{60}\text{Co}$ acquired using the CsI(Na)-PMT detector (a) and the CsI(Na)-PIN detector (b).

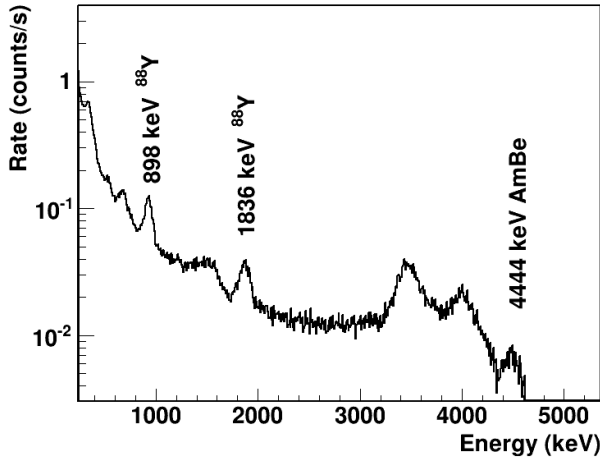


Figure 3.10.: $^{88}\text{Y}+\text{AmBe}$ spectrum acquired using the CsI(Na)-PMT detector

CeF₃_L40-PMT

On the contrary to the previous crystals, the CeF₃ is not a hygroscopic material, therefore its properties are not worsen by moisture and so it does not need to be encapsulated. Thanks to that, the α particles emitted by a radioactive source, ²³⁸Pu in this case, can interact with the crystal and deposit their energy in it. Conversely, both CeBr₃ and CsI(Na) crystals were encapsulated (as it was described in Section 2.3.1) due to their hygroscopicity, so preventing to measure α particles from the ²³⁸Pu source, since they stopped in the sealing material.

The chain of measurement consisted of the CeF₃_L40-PMT coupled to the *Stretch* PCB designed for the CeBr₃-PMT. In the CeF₃_L40-PMT case, in spite of its very fast L.Y. response, after passing by this PCB it behaves linearly, and so the output was directly plugged to the SA CANBERRA 2022 that provided a suited shaped signal to be acquired by the MCA from AmpTek.

The energy resolution of the 662 keV γ -ray photopeak, was measured to be 23 % as can be seen in Fig.3.11, what it is clearly poorer than that obtained with the other crystals, as it can be expected because of its low LY (see Table 2.1).

Concerning the α particle test, in order to ensure that α 's were detected, three configurations were tested:

- a) the α source in contact with the input window of the CeF₃.
- b) a gap of 1 cm of air between the source and the input window of the crystal.
- c) a sheet of paper interposed between the source and the input window of the crystal.

The three acquired spectra can be seen in Fig. 3.11, where the ¹³⁷Cs spectrum is drawn in the same canvas as a reference for the deposited energy. As it is well-known, the α particles energy-loss follow the Bethe-Bloch formula (see Appendix E) being so quickly attenuated in only few air centimetres. In the case of the ²³⁸Pu the α particles are completely attenuated in 3.9 cm length in air [39]. Despite the initial energy of 5.593 MeV, when comparing the α spectrum to the 662 keV γ -rays, the deposited

energy appears even much lower in the configuration (a). This can be explained by the self-absorption in the source and its protection cover, besides the non-linear response to the energy deposition due to the high ionisation density produced very close to the crystal boundary, what it is observed in all scintillators [44, 45]. Concerning the results for the configurations (b) and (c), the energy deposited was lower as expected, because of the interposed material.

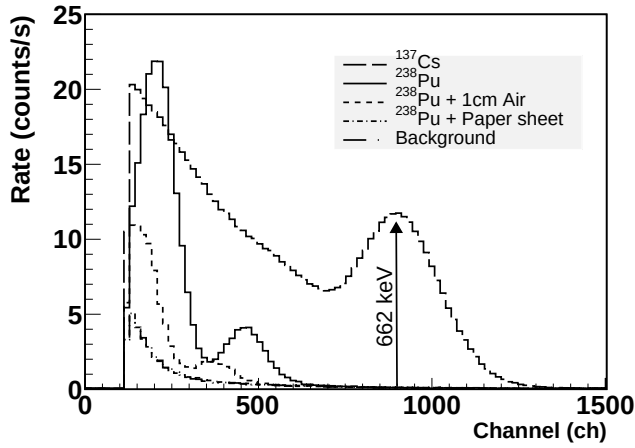


Figure 3.11.: ^{238}Pu spectrum acquired using CeF_3 _L40-PMT for different set-ups. The ^{137}Cs spectrum is added as reference.

The CeF_3 _L50-PMT was also studied for γ -rays emitted from ^{137}Cs source using the same spectroscopic chain aforementioned. The resulting measured energy resolution for the 662 keV photopeak was $R(\%) = 30 \pm 1 \%$ whereas the obtained for the CeF_3 _L40-PMT was $R(\%) = 23 \pm 5 \%$. The difference between both scintillator crystals, apart from their length, was the finishing of the surface that in the case of the CeF_3 _L40 was polished, leading so to a better collection of the photons.

3.1.2. Temperature dependence

The scintillation process is claimed to be temperature dependent, being different for every material [1]. Similarly, the photodetectors based on silicon show a worsening of the detection performance as the temperature increases, due to the increasing noise created by dark current in the output signal. For these reasons, monitoring the temperature plays an important role, since the measured energy resolution might be blurred. Therefore, the CsI(Na)-PMT, CsI(Na)-PIN and CeBr₃-PMT detectors were tested in order to know their behaviour when temperature varies in a range around the room temperature.

The temperature measurements were performed inside a light-tight box (60x50x27 cm³) made of wood covered with copper to avoid the environment RF noise. A thermometer, RS-1315 type K [46], by RS Components, set in contact with the detectors. Its readout was watched by a PC, getting a temperature accuracy of ± 0.5 %. The sampling rate was 0.5 Hz (2 s).

Temperature dependence for CsI(Na)-PMT A set of ¹³⁷Cs spectra was acquired for 15 minutes slots with a time lapse of 3 minutes in between. The average temperature was recorded for every slot. The total measurement time was 6 hours and the maximal temperature variation was 1.8 °C. Fig. 3.12 (a) shows the centroid of the 662 keV photopeak from a ¹³⁷Cs source as a function of the temperature. It is observed that the centroid value, which is related to the detector gain, decreases as the temperature increases, showing a variation of the 1 %/°C in the measured range. The evolution of the temperature over the time is shown in Fig. 3.12 (b). In both figures, the temperature data were averaged over the 15 min time slot of every data taking. Related to the energy resolution, (see the results given plotted in Fig. 3.13), it is concluded that there is not a clear temperature dependence in this temperature range. (Note that the energy resolutions shown in these plots were not accurately corrected by the electronic broadening).

Temperature dependence for CsI(Na)-PIN In order to measure in a wider range of temperature, a cooling brick was introduced inside the

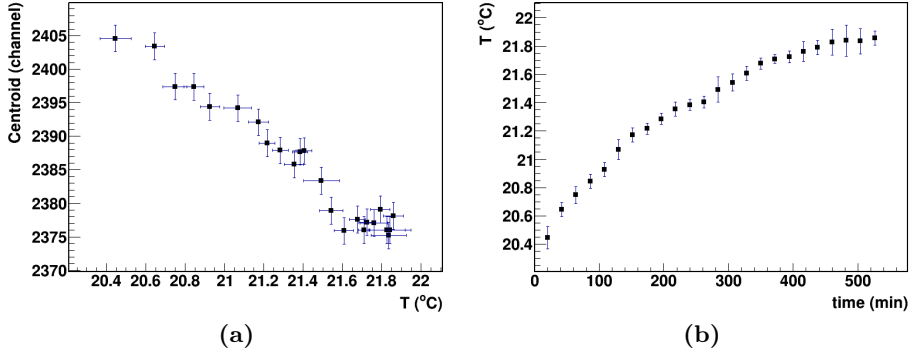


Figure 3.12.: Centroid of the 662 keV photopeak vs temperature (a). Average temperature variation over the measurement time (b) both for the CsI(Na)-PMT detector.

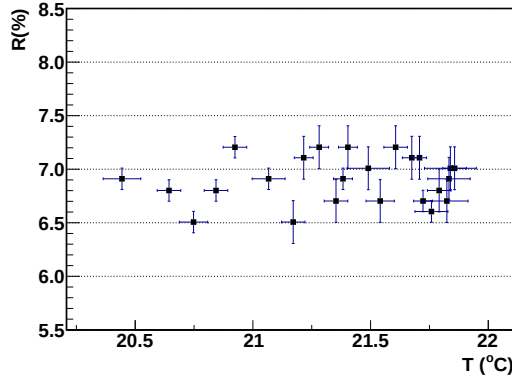


Figure 3.13.: Energy resolution vs temperature for the CsI(Na)-PMT detector.

3. Test results with radioactive sources and cosmic-rays

light-tight box and once the temperature was stabilised at its lowest value, the cooling brick was extracted and the measurements started up. The temperature was sampled at a rate of 0.5 Hz (2 s), while the ^{137}Cs spectrum was acquired for 2 min time slots with time lapses of 1 minute between them. The centroid variation as a function of the temperature as well as the temperature evolution along the time are shown in Fig 3.14 (a) and (b), respectively. Related to the centroid variation, (see Fig.3.14 (a)) a clear trend of the centroid is not observed as it was found in the CsI(Na)-PMT case, nevertheless, an increase of the centroid value is appreciated when the temperature was above 18 °C.

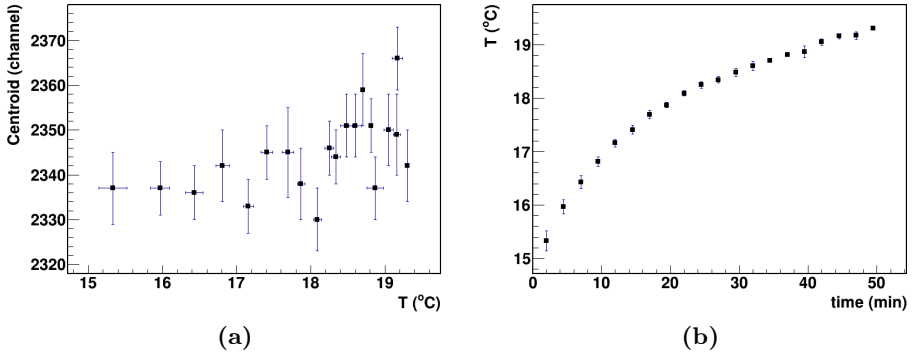


Figure 3.14.: Centroid of the 662 keV photopeak vs temperature (a). Average temperature variation over the measurement time (b) both for the CsI(Na)-PIN detector.

As shown in Fig. 3.15, the energy resolution is not affected by the variation of temperature in the temperature range of interest.

The results of the centroid variation over the temperature can be related to the variation of the L.Y. of the CsI(Na) crystal as a function of the temperature. In Ref. [23], variations of the CsI(Na) L.Y. over the temperature are barely appreciated being consistent with the results obtained for the CsI(Na)-PMT and CsI(Na)-PIN detectors.

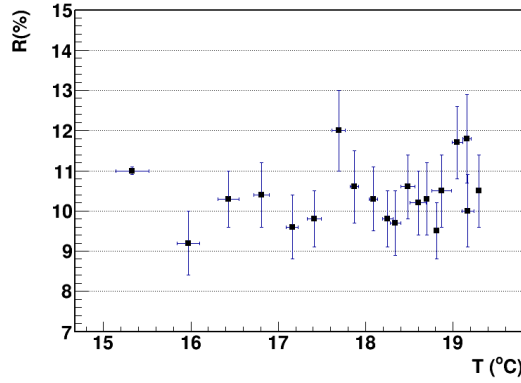


Figure 3.15.: Energy resolution vs temperature for CsI(Na)-PIN detector.

Temperature dependence for CeBr₃-PMT The method to measure the temperature variations was the same than the previously described for the CsI(Na)-PIN. The temperature range measured in this case is shown in Fig. 3.16, where it can be seen how the centroid value for the ¹³⁷Cs decreases as the temperature increases (a), drifting a 1%/°C in the measured range; it can be compared with the variation of the temperature along the time that is shown in (b). Despite the centroid value variation, the energy resolution was not affected by the temperature in the range studied, as it is shown in Fig. 3.17 for the photpeak of 662 keV γ -rays. This agrees with Fig. 9 in Ref. [47], where the deviation of the L.Y. is around 1 % in the range of temperatures here studied.

With reference to the centroid drift, it is notable the trend observed in the CsI(Na)-PMT and CeBr₃-PMT detectors, 1%/°C, in contrast to the CsI(Na)-PIN results. It can be concluded that an accurate monitoring of the temperature is crucial for precise measurements of the deposited energies of the γ -rays, otherwise, the acquired data will have a systematic uncertainty that is not possible to correct for.

3. Test results with radioactive sources and cosmic-rays

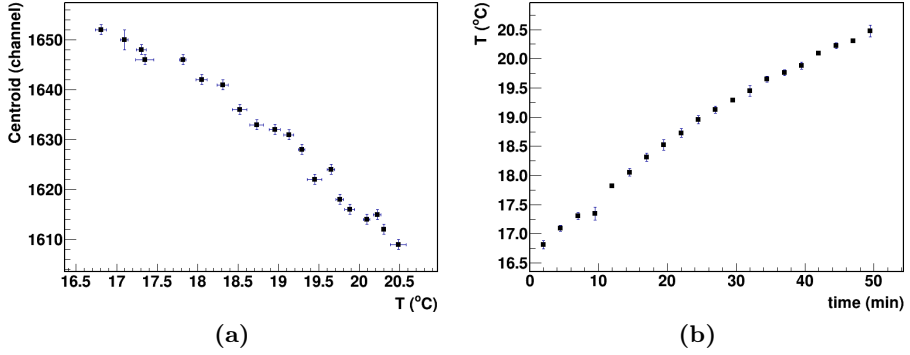


Figure 3.16.: Centroid of the 662 keV photopeak vs temperature (a). Average temperature variation over the measurement time (b) both for the CeBr_3 -PMT detector.

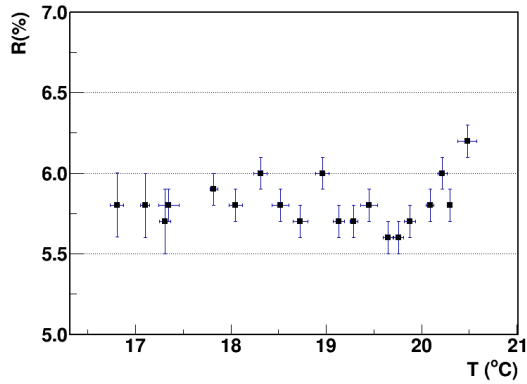


Figure 3.17.: Energy resolution vs temperature for the CeBr_3 -PMT detector.

3.2. Pulse Shape Analysis

The pulse shapes produced by either ionising particles or γ -rays bring out some information about their type. This Section deals with the analysis of the signals produced by the interaction of γ -rays, α particles, β particles and cosmic-muons using the techniques described in Chapter 1.

The signals provided by the scintillator detectors, CeBr₃-PMT, CsI(Na)-PMT and CeF₃_L40-PMT were acquired and digitised by the oscilloscope YOKOGAWA DL9140 (Max. sampling rate 5 Gs/s and Freq. BW = 1GHz) and transferred to a PC for its further analysis.

3.2.1. Time analysis

Firstly, the decay time of each detector was obtained from a fitting method; secondly the shapes of the signals produced by the three different particles mentioned previously were compared; and finally, the time resolution of the detectors was obtained by means of the coincidence method with an ultra-fast organic scintillator detector.

Decay time constants In order to obtain the decay time for each detector, the average profile of each set of signals was obtained calculating the mean value of the amplitude bin by bin. In this case, the signals were produced by the 622 keV γ -rays from a ¹³⁷Cs source. The decay time constants were calculated from exponential fits (as in Eq. 2.8) of the falling edge of the average signal. Fig. 3.18 show the fitting for the three detectors, CeBr₃-PMT, CeF₃_L40-PMT and CsI(Na)-PMT, respectively. The decay time τ_{CeBr_3} is 24 ns (without deconvolving the few ns width of the PMT response) in good agreement with the value provided by the references in Table 2.1. In the CeF₃_L40-PMT case, two components were obtained: $\tau_{1,CeF_3} = 4$ ns and $\tau_{2,CeF_3} = 36$ ns, that are also in agreement with Ref. [21]. Note the rebound in the averages signals from the extremely fast components of the Ce-based detectors, that are produced at the PMT level, even if in this CeBr₃ detector the rebound was minimised by improving the VD. When fitting the CsI(Na)-PMT average profile, two decay time constants have been found : $\tau_{1,CsI(Na)} = 470$ ns and $\tau_{2,CsI(Na)}$

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= 2590 ns. The first constant is in excellent agreement with Ref. [48], where a decay constant of 472 ns is reported, so, ruling out the value of 630 ns given by Saint-Gobain Crystals [23].

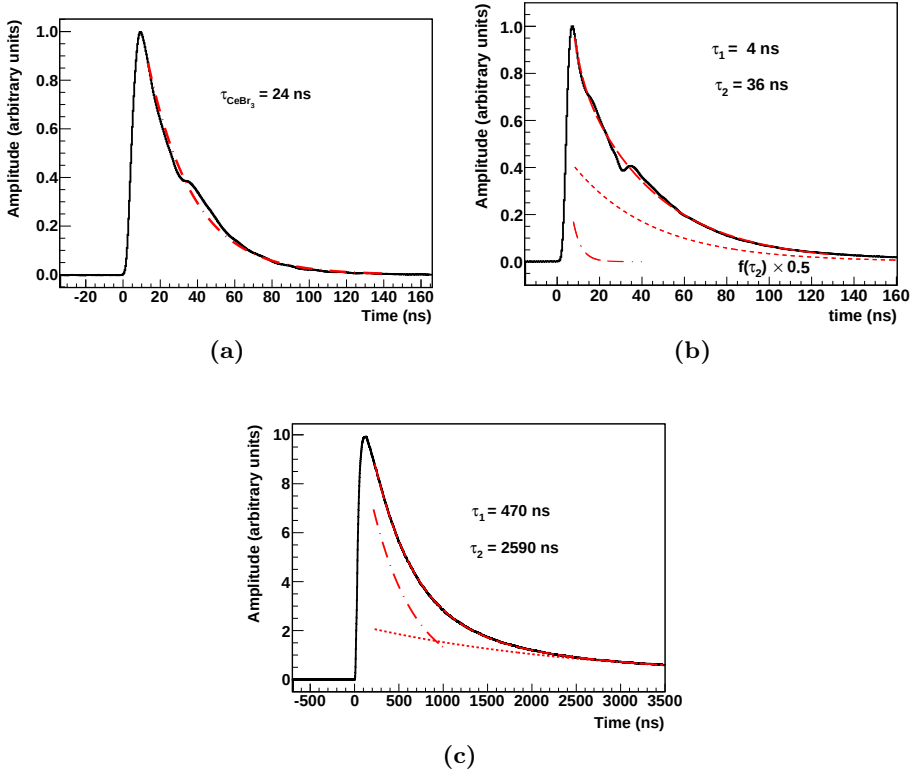


Figure 3.18.: Average pulses for 622 keV γ -rays of CeBr_3 -PMT (a), CeF_3 _L40-PMT (b) and $\text{CsI}(\text{Na})$ -PMT (c). The falling edges were fitted to exponential functions in order to obtain their decay times.

Time resolution A plastic scintillator model EJ-232 from ELJEN TECHNOLOGY, wrapped with a foil of mylar and black adhesive tape, coupled to a PMT mod. R4998 by means of a Silicon Interface Pad. BC-634A, manufactured by Saint-Gobain Crystal, was placed in parallel with the scintillator detector. The signals produced in the plastic detector and in the scintillators detectors were simultaneously registered in the oscilloscope YOKOGAWA DL9140 using a coincidence trigger. Most of these registered events are cosmic- μ 's, the most abundant charged particles at ground level, whose mean energy corresponds to ≈ 4 GeV [18]. The zenith angle of incident muons at ground level is picked around zero and their flux is ~ 1 muon/cm² minute.

In order to obtain an accurate value, the baseline must be deducted from every signal subtracting sample-to-sample the average value of the 30 samples preceding each signal. The time resolution (σ_t) was obtained from the statistical distribution of ($t_{CeBr_3} - t_{Plastic}$), where t_{CeBr_3} is the time obtained by the intersection of the linear extrapolation of the rising edge between 20 and 80 % of the maximum of the signal, and the linear fitting of the baseline. The $t_{Plastic}$ was simply obtained from the time when the signal crossed a constant threshold, because its rise time is shorter than four samples of the digital signal. The distribution was fitted with a gaussian function, as shown in Fig. 3.19, and the obtained the time resolution (σ_t) of the set is 230 ps.

To obtain the time resolution of the CeBr₃-PMT detector, the contribution of the plastic scintillator must be subtracted. It is estimated to be around 100 ps, hence, the time resolution of the crystal scintillator detector was $\sigma_{t_{CeBr_3}} = \sqrt{230^2 - 100^2} = 207$ ps, without corrections by an eventual walk effect associated with the signal amplitude distribution.

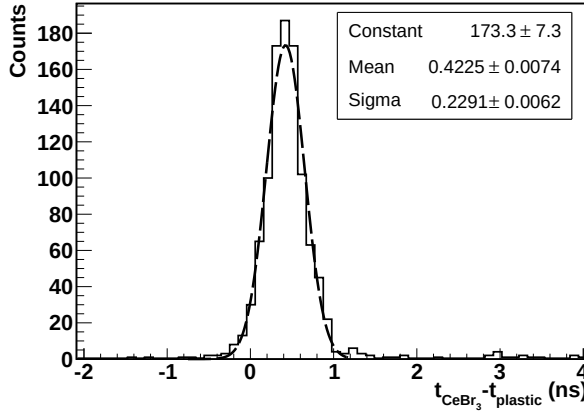


Figure 3.19.: CeBr₃-PMT time resolution distribution fitted to a gaussian function.

3.2.1.1. CsI(Na)-PMT using a Triangular-Barlett filter

The digitised output signals from CsI(Na)-PMT, produced by γ -rays from ¹³⁷Cs and ⁶⁰Co sources, shows an excessive dispersion hindering the observables definition. Smoothing are useful to solve such inconvenient over the raw signals. A Triangular-Barlett filter was chosen with its number of coefficients set to 5. The best results were found when the filter was passed twice over the signal. In Fig. 3.20 a raw pulse is shown in black together with a filtered pulse in orange. It can be appreciated the reduction of the dispersion of the signal points. In Fig. 3.21, the rise region is enlarged to show the improvement in the shape of the original signal after passing one and two times the smoothing filter.

Once the signals have been conditioned, to calculate the CsI(Na)-PMT time resolution, the same procedure that was detailed for the CeBr₃-PMT detector is used. The time distribution of the set is shown in Fig.3.22 where a σ_t of 920 ps was obtained from the gaussian fit for the CsI(Na)-PMT. The time resolution of the crystal scintillator detector is $\sigma_{t_{CsI(Na)}} = \sqrt{920^2 - 100^2} = 915 \text{ ps}$. Here the walk effect produces a worsening of the time resolution resulting in a longer tail of the distribution shown in Fig.

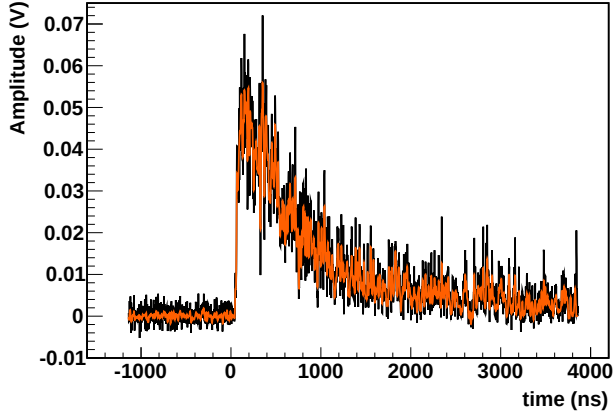


Figure 3.20.: Raw signal from CsI(Na)-PMT (black) and smoothed signal (orange).

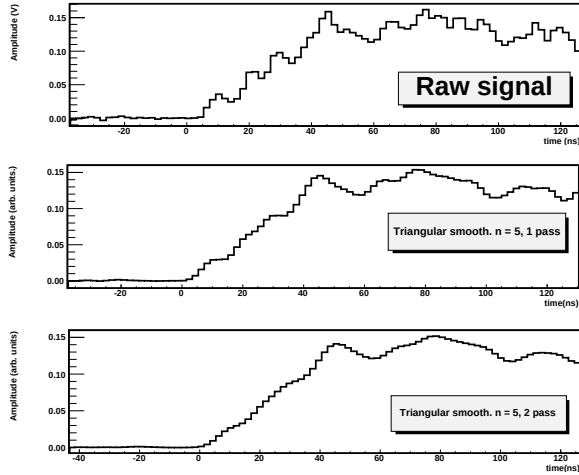


Figure 3.21.: Rise time for a CsI(Na)-PMT pulse. Upper Fig. Original signal. Middle Fig. Signal after one pass 5^{th} order triangular smooth. Lower Fig. Signal after two pass 5^{th} order triangular smooth.

3.22.

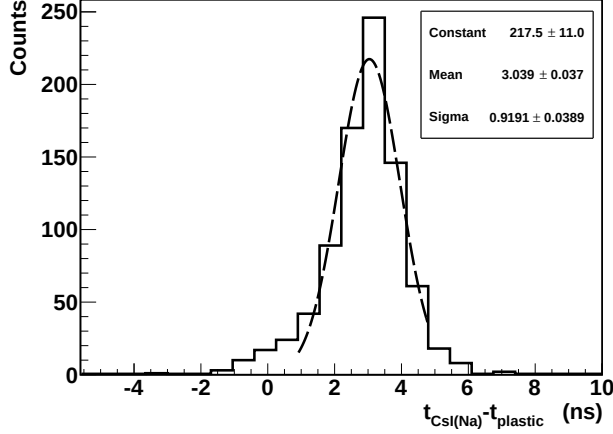


Figure 3.22.: CsI(Na)-PMT time resolution distribution fitted to a gaussian function.

The observable pulse-area have been calculated for the set of pulses. This observable contains information about the deposited energy of the γ -rays emitted from the ^{137}Cs and ^{60}Co sources. In Fig. 3.23 the distribution of this observable can be seen. The three photopeaks, 662 keV, 1173 keV and 1332 keV are well resolved in spite of the scarce statistics and the linearity was checked, as always, taking into account that the last ^{60}Co peak centroid falls at around twice the ^{137}Cs one, within less than 1%. The peak at 662 keV was fitted to a Gaussian function in order to obtain the photopeak energy resolution. The resolution obtained is $R(\%) = 6.7 \pm 0.1$, which is in agreement with the resolution value measured using the spectroscopic chain in Section 3.1.1.

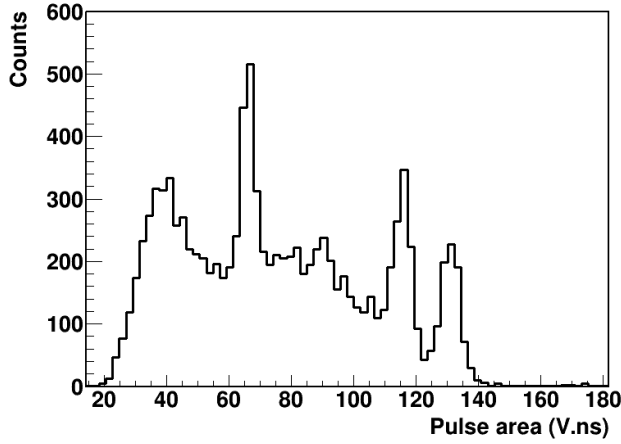


Figure 3.23.: ^{137}Cs and ^{60}Co spectrum obtained after a smoothing of CsI(Na)-PMT signals. The energy resolution for the 662 keV γ -rays is $R(\%) = 6.7 \pm 0.1$. (1 Vns corresponds to 10 keV).

3.2.2. Particle's identification

3.2.2.1. Pulse shape for γ -rays, β particles and cosmic- μ 's

In order to determine the behaviour of the CeBr_3 -PMT and CsI(Na)-PMT detectors when different ionising particles hit the detectors, the average signal profile of a set of signals from three different ionisation particles (γ -rays from ^{137}Cs , β particles from ^{90}Sr and cosmic- μ 's) has been analysed. It is worth mentioning that the maximum amplitude of the cosmic-rays μ 's is around 10 times larger than the corresponding to the 662 keV from ^{137}Cs , proving the wide energy range accepted by both detectors. The setup for measuring cosmic- μ 's is described in next paragraphs.

In Figs. 3.24 the average pulses for each ionisation particle has been normalised to the integral of the pulse. It is remarkable that, both for the CeBr_3 -PMT and the CsI(Na)-PMT, the shape of the pulses does not differ for each ionisation particle.

3. Test results with radioactive sources and cosmic-rays

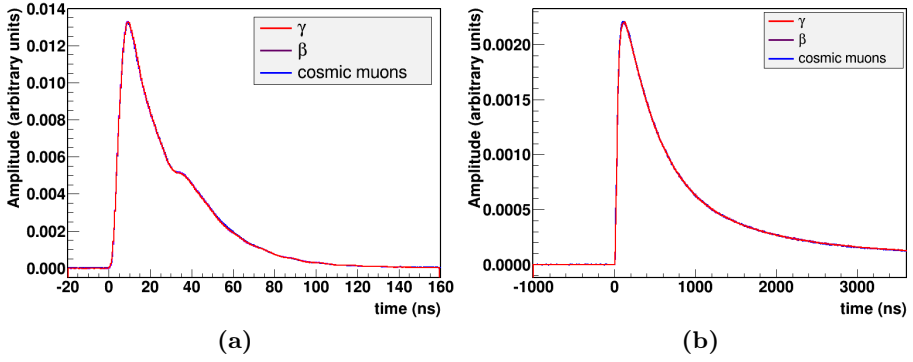


Figure 3.24.: CeBr_3 -PMT average signals for γ -rays, β particles and cosmic-rays muons (a). CsI(Na) -PMT average profile signals for γ -rays, β particles and cosmic-rays muons (b).

3.2.2.2. α/γ identification using CeF₃_L40-PMT

Some scintillators have properties that make them appropriate for particle identification by means of the study of the PSA through the different decay time components of the crystal. CeF₃ crystals have been studied for such purpose in Ref. [49]. In this section, the analysis of the shape of the pulses from an α and γ -ray sources, applying some techniques explained in previous sections are shown. Two sets of measurements were made to this purpose:

- A set of 40000 signals produced by α particles emitted by a ²³⁸Pu radioactive source.
- A set of 40000 signals produced by γ -rays emitted by a ¹⁵²Eu radioactive source.

Both samples were recorded by the oscilloscope YOKOGAWA DL9140 for further analysis.

Average signal identification The averaged profile of each signal set shows different shapes, depending on the incident particle or γ -ray. It can be seen in Fig. 3.25 (a) the averaged profiles from both the α 's and the γ -rays, normalised to their respective areas. Conversely, in Fig. 3.25 (b), the averaged profiles were normalised to the maximum amplitude. In both figures the differences in their shapes lead to define observables looking for the ability of identify the impinging particle kind.

Event-by-event analysis The method consists of the analysis of the raw signals produced by the detector after correcting the baseline through the subtraction of the mean value of the firsts 12 ns recorded by the oscilloscope. Taking into account the differences observed in the average signals, different observables were defined. The observable defined as rise slope corresponds to the slope to a linear fit of the rising edge of each signal. The observable area corresponds to the area from the initial time of the signal, t_{ini} , and t_{ini} plus 140 ns. The results obtained are shown in Fig. 3.26. The observables previously defined are plotted in Fig. 3.26 (a) where the red dots are for the α particles and the blue ones for the γ -rays. It

3. Test results with radioactive sources and cosmic-rays

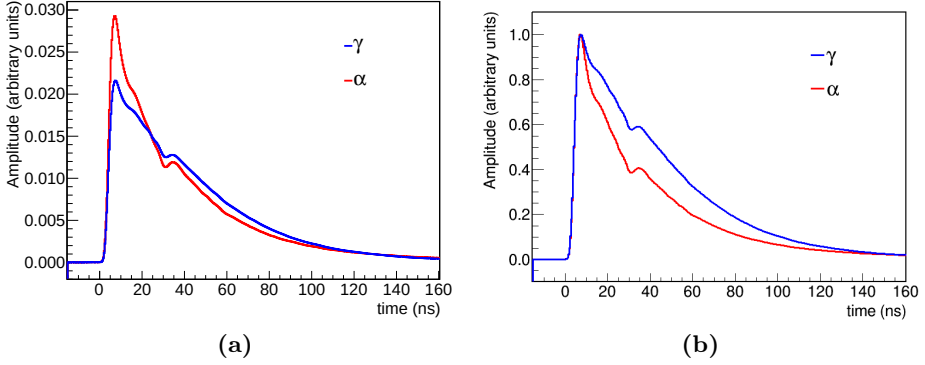


Figure 3.25.: CeF₃_L40-PMT average profile of two sets of signals, one for α particles and one for γ -rays, digitised. In (a) both sets were normalised to each area. In (b) both sets were normalised to each amplitude.

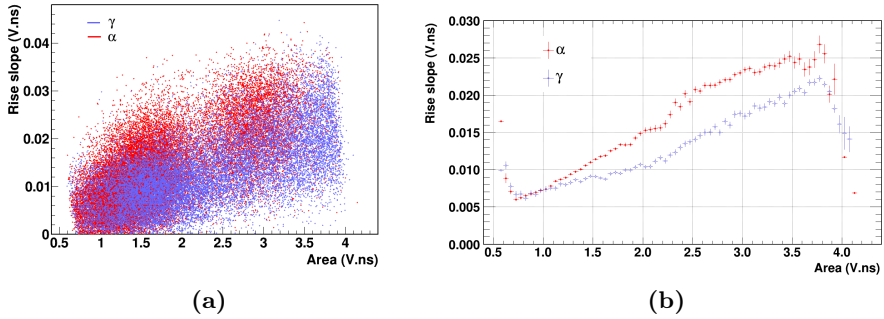


Figure 3.26.: (a) Slope of the rise time of each signal as a function of their corresponding area. (b) Mean slope value as a function of integrated area. Note the splitting between α particles and γ -rays.

is observed that there is a slight difference for both detected. Using the averaged profile again for each particle, Fig. 3.26 (b) it is clearer that from values 1.0 to 3.7 of integral area a identification is possible, however it is not strong enough to discriminate α particles from γ -rays event-by-event. This range is used for study other observables, such as the maximum amplitude and the slope of a linear fitting to the falling slope between 8 and 140 ns after the starting time, t_{ini} , of each pulse. Both observables are referred to the area. For the maximum amplitude-to-area histogram, two contribution can be distinguished, (see Fig. 3.27), however a separation event-by-event is not possible. A similar behaviour is observed for the falling-slope-to-area histogram shown in Fig. 3.28.

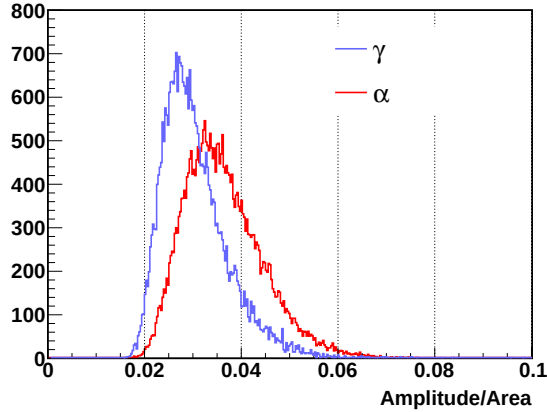


Figure 3.27.: Amplitude-area ratio for γ -rays and α particles.

As it can be seen from Fig 3.26 (b), the pulses produced by α 's show a stronger fast component than those produced by γ 's. Taking into account that the fast component has a shorter wavelength (see Table 2.1), the α/γ separation should be reinforced by using optodevices as much sensitive as possible to the UV side of the spectrum. In this work we were dealing with PMTs having UltraBialkali photocathodes, that are at the top UV sensitivity, but some improvements can be got by using best suited cements in the optical coupling of the crystal with the PMT's window.

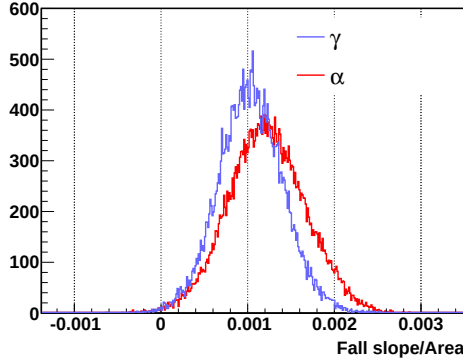


Figure 3.28.: Falling-slope-area ratio for α particles and γ -rays.

3.3. Concluding remarks

The results obtained in this Chapter from the analysis of the γ -ray peaks of a ^{152}Eu source, showed that the linearity of the detector was obtained by using the *strecherPCBs* designed and proposed in Chapter 1,

The results obtained for the energy resolution using different methods are summarised in Table 3.1 :

Scin. detector	CeBr ₃ -PMT	CsI(Na)-PMT	CsI(Na)-PIN
R(E) at 662 keV (Best value)	5.4 ± 0.1	6.4 ± 0.1	9.4 ± 0.3
R(E) at 662 keV (Mean value)	5.6 ± 0.1	6.7 ± 0.1	10.4 ± 0.1
R(E) at 662 keV (^{152}Eu fit)	5.8 ± 0.1	6.3 ± 0.1	10.9 ± 0.1
R(E) at 1 MeV (^{152}Eu fit)	4.6 ± 0.1	5.1 ± 0.1	8.5 ± 0.1
R(E) at 662 keV (FIR)	-	6.7 ± 0.1	-

Table 3.1.: Energy resolution for CeBr₃-PMT, CsI(Na)-PMT and CsI(Na)-PIN scintillator detectors.

The decay times for CeBr₃-PMT, CeF₃_L40-PMT and CsI(Na)-PMT were obtained by a fitting exponentials functions. The values for each detector are: one component for CeBr₃-PMT, $\tau_{\text{CeBr}_3} = 24$ ns, two components for CeF₃-PMT, $\tau_{1,\text{CeF}_3} = 4$ ns and $\tau_{2,\text{CeF}_3} = 36$ ns and two components for CsI(Na)-PMT, $\tau_{1,\text{CsI(Na)}} = 470$ ns and $\tau_{2,\text{CsI(Na)}} = 2590$ ns. It

is remarkable that the obtained value for the decay time of the CsI(Na), $\tau_{1,CsI(Na)} = 473$ ns, in good agreement with [48], ending the controversy found in previous works.

A coincidence method, using a very-fast plastic scintillator and the crystal scintillator detectors, was applied to determine the time resolutions for the CeB₃-PMT and CsI(Na)-PMT detectors. The values were 207 ps and 915 ps respectively. The triangular-Barlett filter described in Section 1.2, was applied to smooth the signals for the CsI(Na)-PMT improving so the time resolution.

A method is proposed in order to discriminate α particles from γ -rays. The study of the averaged profiles produced by both kind of radiations shows differences but, nevertheless, the resolution obtained in the observables here defined does not give accuracy enough to discriminate such particles event-by-event.

4. Beam-tests in the n_TOF experiment

The significantly high flux of neutrons attainable from the high-intensity short-pulsed 20 GeV protons on the n_TOF spallation target, together with the very special characteristics of the two lines of neutron time-of-flight, makes the n_TOF measurements superseding those at any other neutron source world around. These kind of facilities are devoted to enlarge and improve the existing libraries on nuclear data, that are at the foundations of Nuclear Science, because the accurate knowledge of nuclear evaluated data is essential for the deeper understanding of many processes occurring in Nature. In particular, for disentangling the puzzle of the nucleosynthesis of elements beyond Iron in stars, via the s- and r-processes [50] and, on the other hand, for boosting the development of technologies related to the better functioning of present nuclear reactors [51] as well as the future ones aiming at minimizing the production of nuclear waste or even at burning it [52] in Fast reactors, namely in ADS [53]. This makes it necessary to perform new and more accurate measurements of many isotopes and reactions, which are summarized, for instance, by the Nuclear Energy Agency in its High Priority Request List [54].

In Chapter 3, the detectors developed in this thesis work have been characterised in a lab bench, where the measurement conditions can be largely controlled, whereas in an experimental area devoted to the study of nuclear reactions the environment becomes challenging when performing the measurements. This Chapter deals with the measurements related to the n_TOF facility at CERN that have been done in the frame of this Thesis work. So that, the scintillator detectors previously characterised were moved to the n_TOF facility at CERN in Geneva (Switzerland), in order to test their behaviour in a real environment, providing new information for their future possible use in new detectors.

The detectors CeBr₃-PMT and CsI(Na)-PMT in the n_TOF facility were firstly tested by measuring the prompt γ -ray emission in the neutron

capture reactions $^{197}\text{Au}(n,\gamma)$ and $^{nat}\text{Ag}(n,\gamma)$. Then, in addition to this, the prompt- γ produced in the neutron-induced fission reaction $^{235}\text{U}(n,f)$ were measured in coincidence with the PPAC gaseous chambers.

In the next Section, a brief description of the n_TOF facility is given and next the measurements and results obtained on the prompt γ -rays from neutron capture studies will be presented. In Section 4.3 will be discussed the analysis of the prompt γ -rays from fission reactions, whereas the work done to characterise the γ -flash are shown in Section 4.4.

4.1. n_TOF Facility

The neutron time-of-flight facility n_TOF features a white neutron-source produced after nuclear spallation reactions in the hadronic cascades originated in a huge lead target by protons bunches of 7 ns (rms) from the Proton Synchrotron (PS) of 20 GeV/c, having 7×10^{12} ppp, at a repeating rate of 0.8 Hertz. The facility, aiming primarily at the measurement of neutron-induced reaction cross sections, was operative at CERN between 2001 and 2004, and then underwent a major upgrade in 2008 (See Ref. [55] and references therein). The required high energy-resolution is attained by making the pulsed neutron-beam, that spans over an available energy range wide of ten decades, to travel a distance long of 185 m before reaching the sample under study. In this technique the kinetic energy of the neutrons is so determined from their time of arrival at the measuring station, ranging from some 600 ns, for those travelling close to the speed of light, up to around 80 ms for the thermal ones.

The lead spallation target, whose dimensions are 40 cm long and 60 cm in diameter, is sketched in Fig. 4.2. Two different water layers are beside the target: one of 1 cm of distilled water acting as cooler and another of borated water, 4 cm wide, that works as moderator of the initial fast neutrons to enhance the low energy part of the spectrum. A wider and flatter energy spectrum, from thermal energy to relativistic neutrons, was so obtained (see Fig 4.3).

During the spallation process, besides neutrons, a huge quantity of particles are produced due to both electromagnetic and hadronic processes.

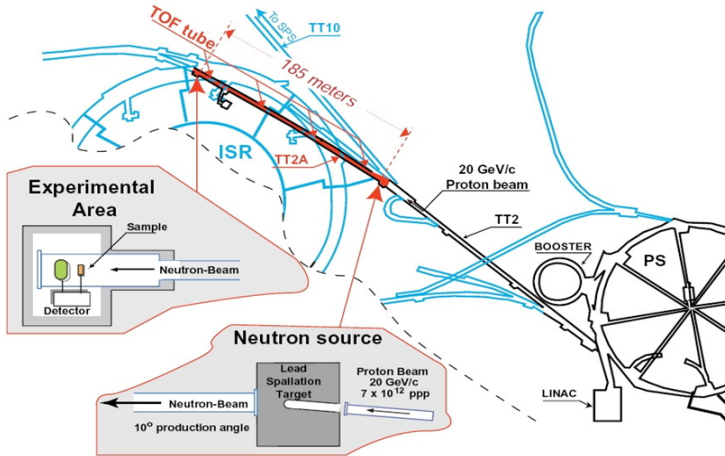


Figure 4.1.: Schematic view of the n_TOF facility at CERN.

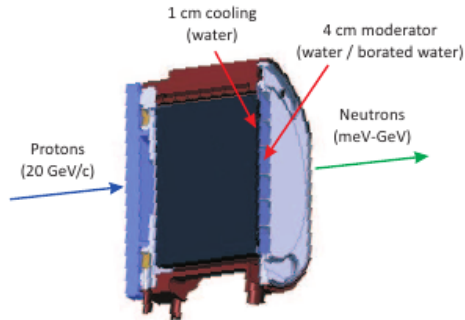


Figure 4.2.: Lead spallation target.

Therefore, the neutron beam line is tilted 10° respect to the proton beam, in order to allow the primary proton beam to scape.

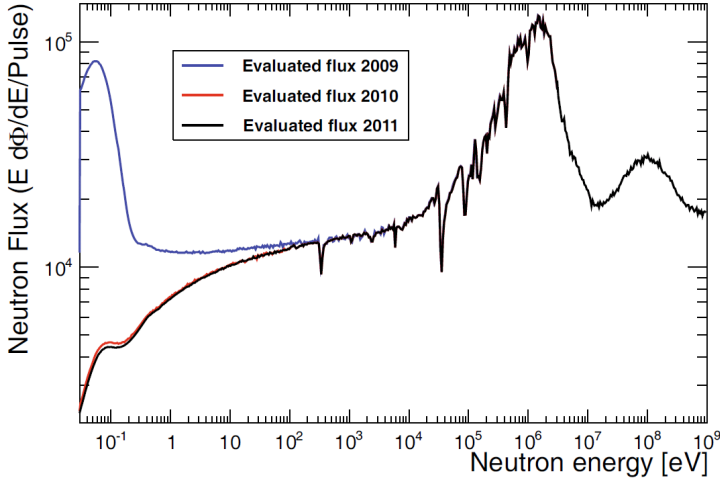


Figure 4.3.: Evaluated neutron flux for different spallation targets in the EAR1 [56].

To sum it all up, the n_TOF facility provides a very high instantaneous intensity of around 10^7 neutrons/pulse in a collimated beam of 3.5 or 10 cm, and an excellent energy resolution in the complete energy interval of interest. Due to these characteristics, the n_TOF facility stands today among the world leading facilities for measuring neutron-induced reactions.

Beam line to EAR1

This beam line was done taking advantage of a service tunnel already existing at CERN. It goes from the spallation target to the Experimental Area 1 (EAR1), having a length of 182.3 meters with different elements that are placed all along the beam line, as sketched in Fig. 4.4. In order to clean-up the neutron beam a 3.6 Tm sweeping magnet (200 cm in length, 44 cm gap) at 145.4 m, deflects the charged particles that are in the beam. After this magnet, at 151 m, a 3.2 m thick iron wall plays a role as μ shielding because of the in-flight decay products (mainly μ s and ν s) from the $K^\pm$ s and $\pi^\pm$ s coming from the spallation process. The

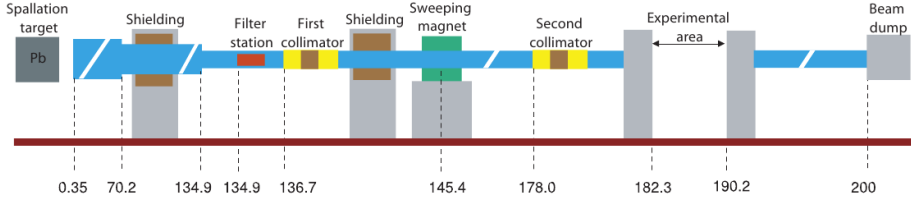


Figure 4.4.: Beam line to the EAR1. The components and the tube sections are anathematised. Distances are referred to the centre of the spallation target (not in scale).

coarse shielding at around 80 m and two collimators are included in the beam-line in order to get a well defined neutron beam, as clean of halo as possible. The first collimator is at 136.7 m and the second one at 178 m. Two configurations for the second collimator can be chosen, depending on the measurement requirements: a 18 mm diameter with 235 cm of steel plus 50 cm of borated polyethylene is chosen to measure capture reactions, and a 80 mm diameter, with 50 cm of borated polyethylene, plus 125 cm of steel, plus further 75 cm of borated polyethylene, to measure fission reactions. A 3 m width broad concrete wall separates the previous elements from the EAR1. Finally, a 1.6 m deep concrete wall at 190 m separates the EAR1 from the DAQ area, where the experimental set-up is deployed; the beam line prolongs some 10 m from the end of the EAR1, performing a scape-line ending in a borated polyethylene cube at 200 m, to dump the beam [55] in order to minimise the back rebounding neutrons [57].

Beam line to EAR2

In summer 2014, a new neutron beam line was added to the *n*_TOF facility, going to the Experimental Area 2 (EAR2). It is vertically oriented, starting on top of the spallation target, which is there surrounded by only the layer of 1 cm of de-mineralised water acting as coolant. The entrance window is made of an Al foil coupled to the vacuum pipe flange.

Different elements are distinguished along the beam pipe, at distances taken from the center of the spallation target. The first collimator at 7.4 m above the target, consisting of a Fe cylinder 1 m in length with 20 mm

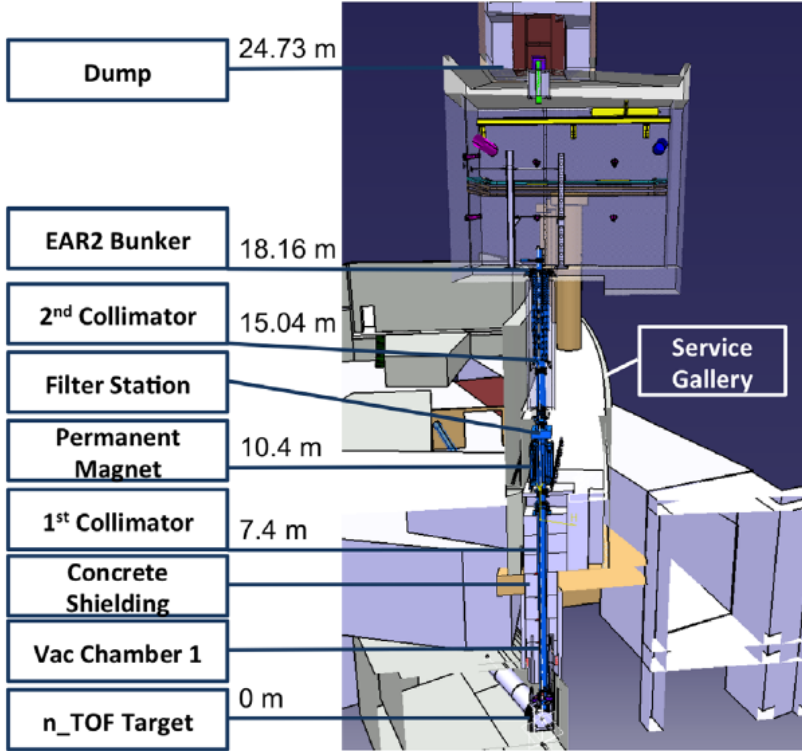


Figure 4.5.: General layout of the beam line to the EAR2. The different elements with the position of their entrance are indicated on the left [58].

of inner diameter. At 10.4 m a permanent dipole magnet is installed to deflect the charged particles produced during the spallation process. The magnetic field created is 0.253(4)T in the centre of the magnet, whose length is 1.134 m. The integrated field of the magnet is 0.287 Tm. The dipole magnet inner gap is 340 mm, where the vacuum pipe is passing-through. A second collimator is installed at 15.04 m inside a large vacuum vessel with 680 mm outer diameter. The collimator consists of 2 m Fe and 1 m borated polyethylene (B-PE), where a core of boron-carbide (B-C) cylinders are inserted in the last 0.4 m. The diameter of the collimator is variable following a conical shape, decreasing as the distance is closer to the experimental area, from 70.0 to 21.8 mm. The exit of the second collimator is situated at 120 mm below the EAR2 floor. The focal point, which is theoretically the position of the narrowest spatial beam profile, is positioned at 1.08 m from the floor of the EAR2 which is located at 18.16 m from the spallation target while the experimental ceiling is at 23.66 m. The first meter from the floor is devoted to a neutron flux monitor, which is installed inside the vacuum pipes in the lowest section of the EAR2, and a Pb shielding. The different detection systems can be placed thanks to a set of support structures which are mounted on a pillar system the exit of the neutron beam. Finally, the beam dump is hanging from the roof of the building, being designed to respect the limits of dose rate of radiation protection for low-occupancy areas, 2.5 $\mu\text{Sv/h}$, outside the building. It consists of three layers: B-PE core to slow down and to capture neutrons, the core is surrounded by Fe blocks to absorb the fast neutrons and photons of the beam and finally the beam dump is shielded by concrete. Fig. 4.5 sketched the beam line 2. See Ref. [58] for further details.

In order to minimise the background, the following considerations have been taken into account:

1. From 0.9 m above from the spallation target up to 7 m concrete elements are placed.
2. 4 tons of stainless steel spheres formed the shielding in the middle part of the beam line, from 12.6 m to 18.4 m.
3. Plates of lithium-polyethylene surrounding the beam pipe are placed on the floor of the EAR2 to absorb thermalised neutrons.
4. 57 cm of Pb disks are placed after the exit of the second collimator

inside the vacuum chambers to reduce the γ background coming from the last section of the collimator.

5. Shielding elements such as Pb, B-PE and B₄C were placed in the last vacuum beam-line, fixed to the roof of the EAR2, just before the beam dump in order to reduce the photons and neutrons streaming back to the detectors.

4.1.1. Detectors at the n_TOF facility

A wide variety of detectors are used at n_TOF for performing experiments to measure nuclear data from neutron-induced reactions as radiative capture, fission or light-nuclei spallation. Among these are: solid-state detectors, such as the silicon based neutron beam monitor [59] or CVD diamond detectors [60]; scintillation detectors, including a TAC made of BaF₂ crystals [61] and the C₆D₆ liquid scintillators [62] used for radiative capture detection; and, finally, gas-ionisation detectors, as the MicroMegas-based detectors [63], H19, a calibrated fission chamber from the Physikalisch Technische Bundesanstalt [64], or different sets of Parallel Plate Avalanche Counters, that are deeper described below.

Parallel Plate Avalanche Counters, PPAC

As already commented, the studies performed in this work were done using the scintillating detectors in parallel with the PPAC detectors that allow identify the (n,f) reaction events. Let's so to introduce the PPACs functioning and how they were used to our purposes.

Parallel Plate Avalanche Counters (PPAC) [65, 66, 67] belongs to the gaseous detectors type that operate in proportional mode after application of an electric field between two parallel plates surrounded by a gas at low pressure. The type of gas in combination with its pressure and the distance that separates the plates, play an important role when detecting the charged particles passing through the detector.

In the proportional regime, the charged particle creates an specific number of pair electrons and positives ions that are drifted to the anode and the cathode respectively. During such drift, both the electrons and ions

are able to create new pairs of electrons and ions. Such secondary electrons are accelerated by the electric field and so it can ionise molecules, and new electrons will be released creating a swarm of electrons that drifts to the anode, with a characteristic velocity given by the type of gas. The avalanche produced, known as Townsend avalanche is proportional to the primary charge created by the ionising fission fragment and induces charge both in the anode and in the cathodes resulting in a current signal where the electron drift contribution is much faster than that of the ions, because the mobility of the ions in a gas is well below 1% of the electrons one. Following the Townsend model, the number, n , of electron/ion couples should grow as:

$$\frac{dn}{n} = \alpha \cdot dx \quad (4.1)$$

where α is the first Townsend coefficient. In the case of a parallel plate geometry, the coefficient α is a constant and the solution to the previous equation is:

$$N(x) = N(0) \cdot e^{\alpha x} \quad (4.2)$$

and from this rough approximation we can see that the final size of the electron swarm is depending on the depth of the fission-fragment track in the detector gas, what it is difficult to modelling.

The gas used in the PPAC setup is C_3F_8 , a non-flammable gas. The PPAC configuration adopted is illustrated in Fig 4.6 based on the model proposed in Ref [65]. The active detection area is a 20 cm x 20 cm surface made of 1.5 μ m Mylar material coated with aluminium on each side. Both cathodes have the same size, however, the mylar surface is not continuous but stripped with a 2 mm pitch: one horizontally and the other vertically what allows the tracking of the FF traversing the PPAC detector, see Fig. 4.6. A gap of 3.2 mm is in between the anode and each cathode. The bias voltage applied is 300 V/cm.mbar.

Signal induced in both the anode and the cathodes are amplified by the associated electronics set in the plastic frame. In the case of the cathodes a delay line, connected to a preamplifier, is set at the end of the strips, being decoupled by capacitors of pF welded between the strips. The position of the avalanche is obtained by measuring the delay time between the pulse

on the anode and the pulses propagating along the delay lines. The main advantage of the delay line is the reduction of readout channels: two per cathode instead of one per strip.

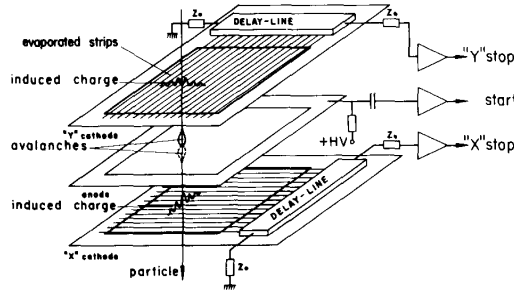


Figure 4.6.: PPAC schematic view. An anode in between of two stripped cathodes and their read-out electronics are represented. Note the induced charge in the three planes [65].

A PPAC, as a low density gas detector working on the proportional regime, is not efficient for the detection of γ -rays since the probability for the γ radiation to interact in the gas is small. However, the detection efficiency for FF fragments entering the active volume reaches up to 100%.

PPACs offer great improvements over other types of detectors with regards to their time resolution, typically well below 1 ns (see Ref. [66] and references therein). Since PPACs are almost insensitive to γ -rays, they are widely used to detect fission fragments, even in a background with high levels of γ -rays or light charged particles. Unlike scintillator or semiconductor detectors, they are not damaged by radiation and can support high counting rates; this makes them useful for in-beam measurement of neutron and proton-induced reactions. In this work, it was taken advantage of these unique properties for tagging fission events when looking for coincidences with our scintillator detectors (see Section 4.3).

4.1.2. DAQ system

The n_{TOF} data acquisition system must deal with signals coming from different detectors, having different shapes and characteristics, but for all of them its time stamp is crucial to be related event-by-event with the

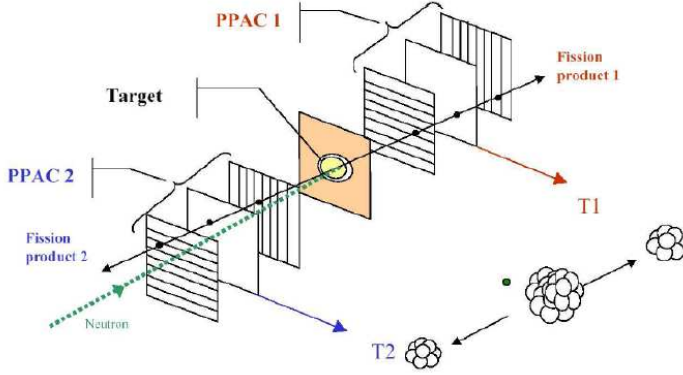


Figure 4.7.: Schematic working of a PPACs detectors.

neutron time of flight, after every proton pulse from the CERN-PS. So that, a high-performance digital data acquisition system has been developed for the management and storage of the huge amount of electronic detector signals. The system is based on flash analog-to-digital (fADC) modules, manufactured by Acquiris, with four input channels, ensambled in a cPCI crate housing up to 4 modules. The number of available channels is 60 in EAR1 and 32 in EAR2. The system has been recently upgraded to get an amplitude resolution of 8 to 12 bits, operating at sampling rates typically ranging from 100 MHz to 2 GHz, with a memory buffer of up to 175 MSamples, allowing for an uninterrupted recording of the detector output signals during the time-of-flight range of approximately 100 ms. The fADC's starting time is picked-up from the CERN-PS proton bunches but when a time accuracy below 1 ns is required, the γ -flash from the lead spallation target is used to get so the full time resolution (see Section 4.4). A fast zero suppression algorithm can be performed in order to reduce the large quantity of data to be stored. When this option is chosen, once one detector's signal rises above a user-given trigger value, a data frame is selected containing only a given number of pre-samples and post-samples, before and after the selected signal. A detailed description of this DAQ can be found in [68].

Once stored in digital form, in the memory blocks allocated to them, the electronic signals have to be off-line analysed, in order to obtain the

4. Beam-tests in the n_{TOF} experiment

time-of-flight and pulse information for each detected pulse. The analysis

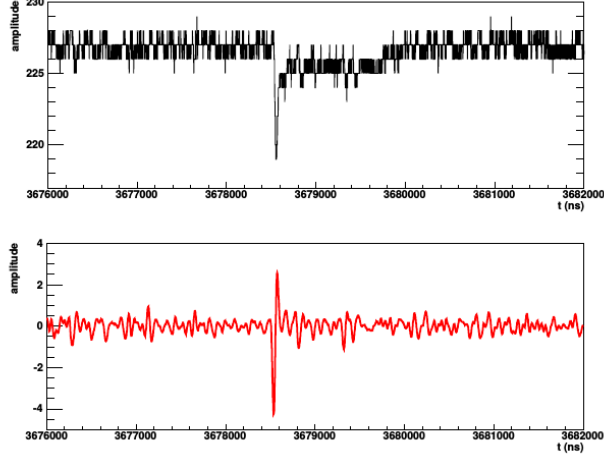


Figure 4.8.: Top panel: PPAC signal from an anode. Bottom panel: Filtered PPAC signal used for the analysis [66].

routine for the PPAC detectors [67, 69, 70], removes the high-frequency oscillations in the baseline by means of a peak recognition function based on a derivative filter (Hanning filter). The original signal takes a bipolar shape after it has been derived, which it can be seen in Fig. 4.8. Peak discrimination is done by applying certain conditions to the derived signal. The negative part must arrive first, to ensure the negative polarity of the signal. The bipolar signal must then cross two thresholds (one positive and one negative) which were determined from the study of real signals. Additionally, the time between both peaks of the derived signal and the ratio of both amplitudes are limited to certain values. Signals fulfilling all these requirements are kept and two parameters are stored for them in the DST file: the zero-crossing time of the bipolar signal and its peak-to-peak amplitude. The same pulse shape analysis is applied to all the PPAC detector channels.

4.1.3. Neutron energy calculation

The neutron kinetic energy is calculated from the path length and the time-of-flight, according to the relativistic formula:

$$E_n = m_n c^2 (\gamma - 1) \quad (4.3)$$

where m_n is the rest mass of the neutron, c the speed of light and γ the Lorentz factor. Expressing the Eq. 4.3 in terms of the flight path, L , and the time of flight, t , the equation leads to

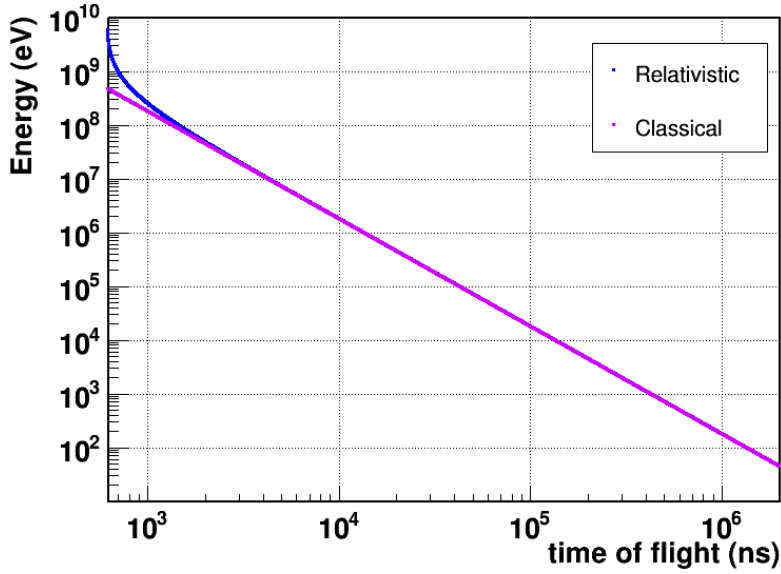
$$E_n = m_n c^2 \left(\sqrt{\frac{1}{1 - \frac{1}{c^2} \left(\frac{L}{t}\right)^2}} - 1 \right) \quad (4.4)$$

For neutron energies below a few MeV , the classical expression for the kinetic energy, which corresponds to the first term of the Taylor series expansion of Eq. 4.4, can be used:

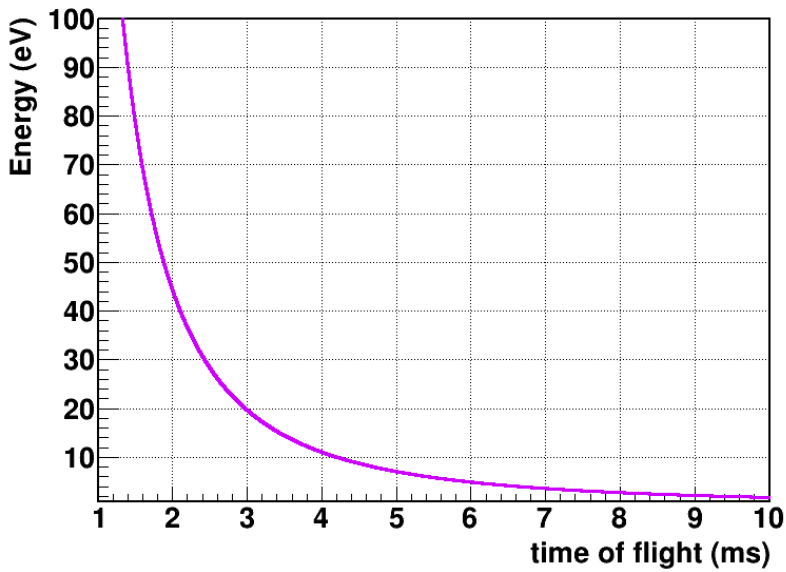
$$E_n \approx \left(\alpha \frac{L}{t} \right)^2 \quad (4.5)$$

where $\alpha \simeq 72.29$ when L is expressed in m, t in μs and E_n in eV.

In Fig. 4.9 (a) the difference between the relativistic and classical approximation can be appreciated. In (b), the relation neutron-energy time-of-flight is shown in the range where the prompt γ -rays from (n,γ) and (n,f) reactions are studied in this work. The kinetic neutron energy was calculated by using $L \simeq 185$ m which corresponds to the flight path of EAR1 ($L \simeq 19$ m for EAR2).



(a)



(b)

Figure 4.9.: Neutron energy as a function of time of flight. Note in (a) the difference between the relativistic (blue line) and the classical formula (violet line) below $10 \mu\text{s}$. In (b), the neutron energy as a function of the time of flight in the region used to detect prompt γ -rays from neutron induced reactions.

4.2. Prompt γ -rays from (n,γ) reactions

One of the main topics covered by the n_TOF research programme is the study of (n,γ) reactions. The prompt γ radiation associated to this radiative neutron capture was in this work firstly used to characterise our scintillator detectors in a real environment, comparing the results with those obtained in the lab-bench.

4.2.1. Neutron capture reactions $^{197}\text{Au}(n,\gamma)$ and $^{nat}\text{Ag}(n,\gamma)$

Neutron capture reactions from two samples of $5.8 \cdot 10^{-4}$ at/b of ^{197}Au and $6.91 \cdot 10^{-4}$ at/b of ^{nat}Ag were measured using the CeBr_3 -PMT and $\text{CsI}(\text{Na})$ -PMT detectors. In the 2012 campaign both scintillators were placed in EAR1, at 30 cm from the targets, accepting those photons forming an angle of 65° from the beam axis as shown in Fig. 4.10.

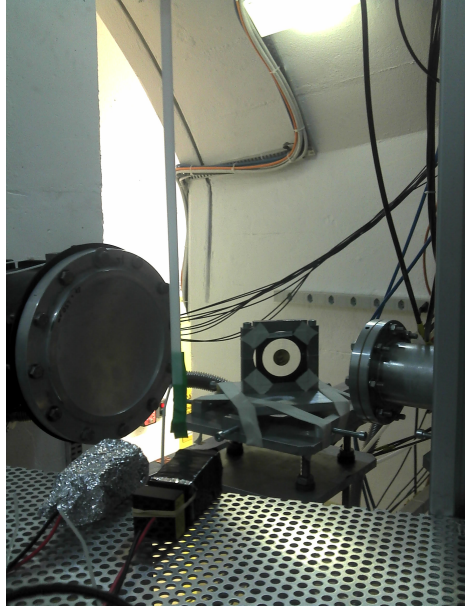


Figure 4.10.: Neutron capture set-up for CeBr_3 -PMT and $\text{CsI}(\text{Na})$ -PMT in EAR1.

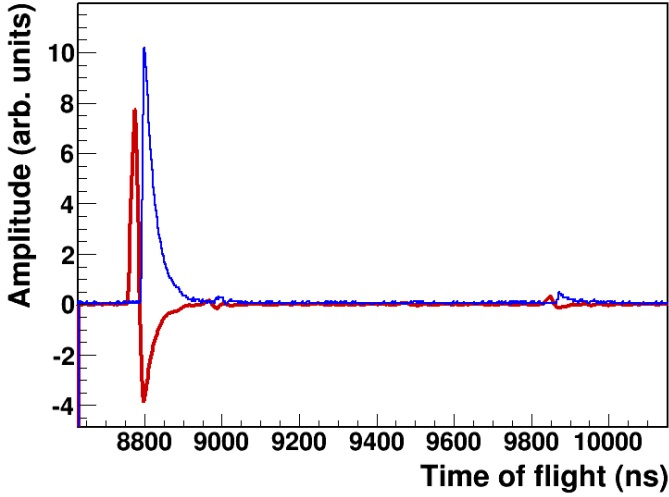
4.2.2. Data analysis

The capture energy spectrum has been calculated through the time difference of the γ -ray impact on the scintillator detector and the time of the γ -flash as a reference time. The neutron energy selected for this study ranges from 0 to 100 eV, where the stronger capture resonances are found for both ^{197}Au and ^{nat}Ag . To find the time-of-flight of the signal produced by the γ -rays a FIR trapezoidal filter was used.

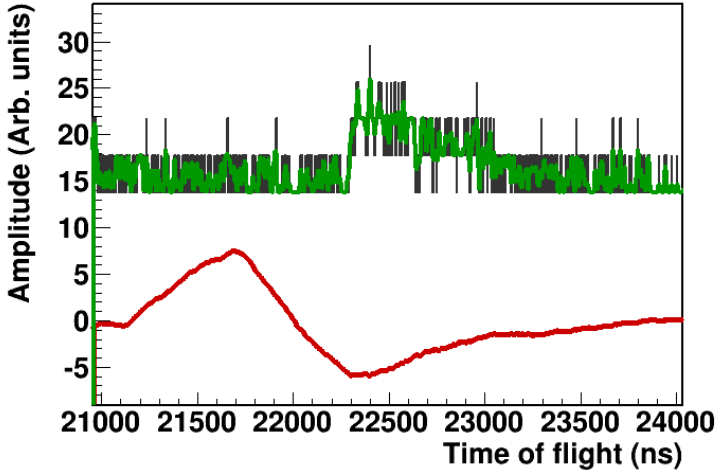
These filters, one dedicated to the CeBr_3 -PMT signals, another to the $\text{CsI}(\text{Na})$ -PMT ones, make signals better shaped and baseline restored. Two examples of filtered signals can be seen in Fig. 4.11. In Fig. 4.11 (a), the blue line corresponds to the output from the fADC showing a couple signals from the CeBr_3 -PMT detector (two very different amplitude signals have been selected for comparison). The red line is the bipolar filtered signal, showing a smoother baseline. In Fig. 4.11 (b), a original signal from the $\text{CsI}(\text{Na})$ -PMT detector (black line) shows a baseline shift. The green line is the smoothed signal before passing the bipolar filter. The red line corresponds to the bipolar FIR filtered signal, where the baseline shift has been restored. As it is observed in both filters, a delay time is present in the filtered signals due to the filtering processes. Such effect must be corrected in order to obtain an accurate measurement of the time-of-flight. The filter parameters used in these cases are shown in Table 4.1.

Acquisition Sampling Rate	500 MS/s	
Scintillator detector	CeBr_3 -PMT	$\text{CsI}(\text{Na})$ -PMT
L (ns)	16	560
G (ns)	4	56
Delay time (ns)	20	1176

Table 4.1.: Trapezoidal filter parameters for CeBr_3 -PMT and $\text{CsI}(\text{Na})$ -PMT detectors used in prompt γ -rays measurements.



(a)



(b)

Figure 4.11.: Trapezoidal-filtered signals for CeBr_3 -PMT and $\text{CsI}(\text{Na})$ -PMT. In (a), the blue line corresponds to a couple of the events from CeBr_3 -PMT registered by the n_TOF DAQ. The red line is the filtered signal, showing a constant time offset. In (b), an original signal from $\text{CsI}(\text{Na})$ -PMT (black line) shows a baseline shift. The green line is the smoothed original signal showing a better shape. The red line corresponds to the trapezoidal-filtered signal. Note the baseline shift correction.

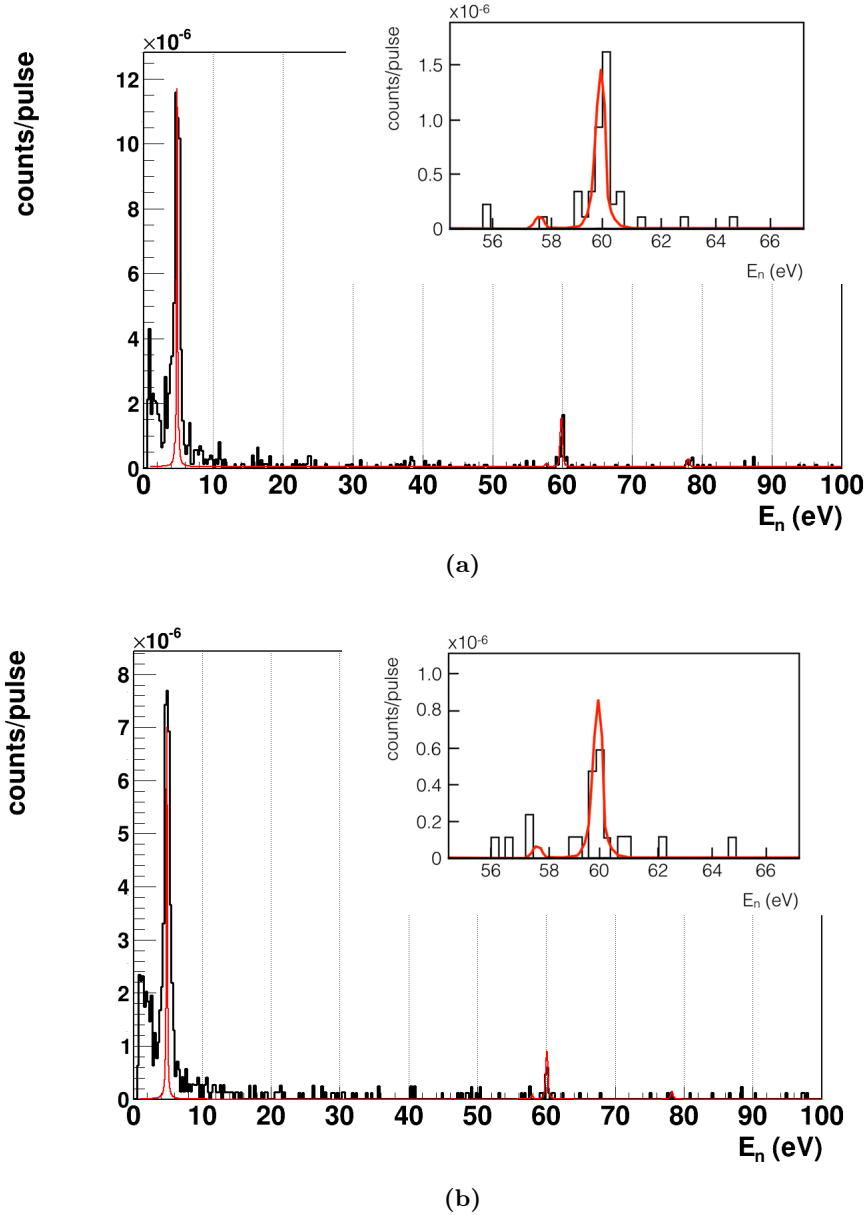


Figure 4.12.: Black line: Measured counting rate distribution corresponding to the $^{197}\text{Au}(n,\gamma)$. Red line: ENDF/B-VII.1 cross section evaluation scaled for comparison with the measured data. (a) corresponds to CeBr₃-PMT measurements, (b) corresponds to CsI(Na)-PMT measurements.

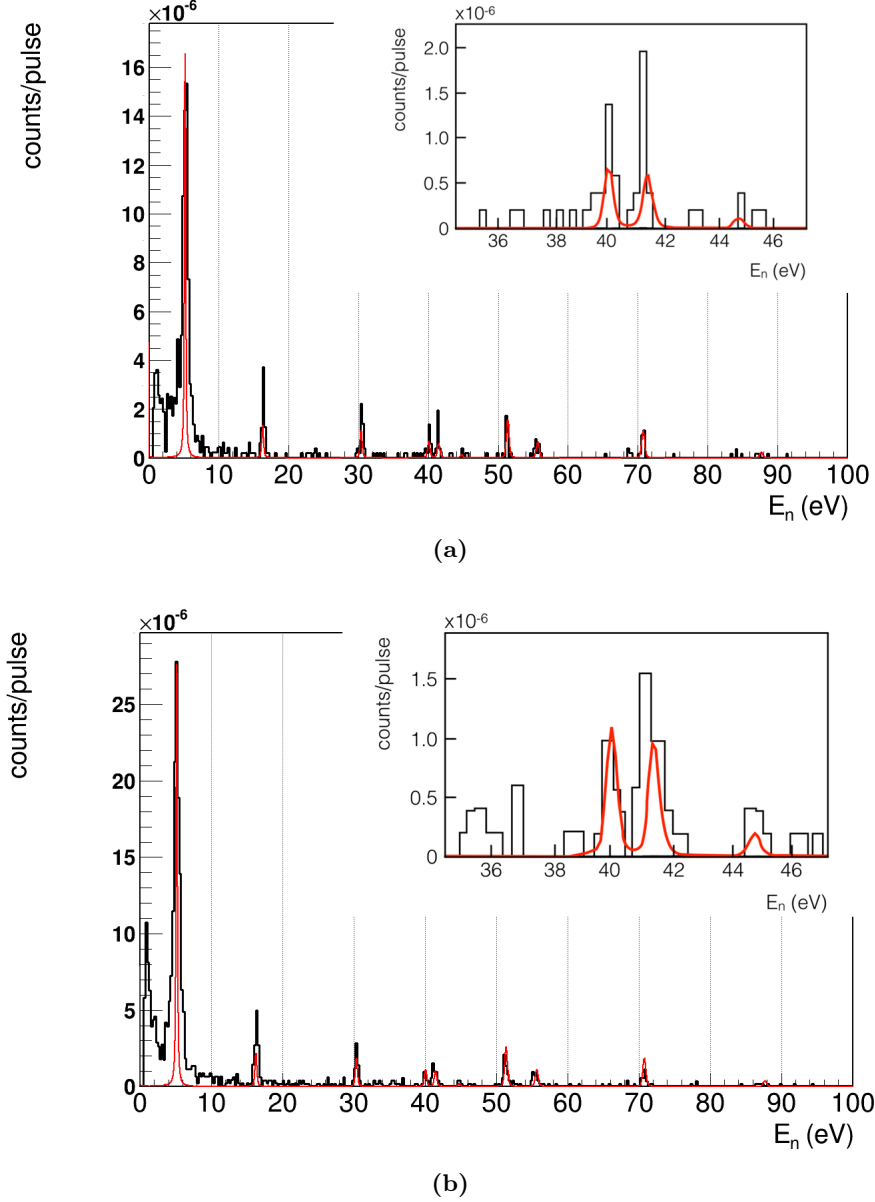


Figure 4.13.: Black line: Measured counting rate distribution corresponding to the $^{nat}\text{Ag}(n,\gamma)$. The data were corrected by the neutron flux. Red line: CENDL-3.1 cross section evaluation scaled for comparison with the measured data. (a) corresponds to CeBr₃-PMT measurements, (b) corresponds to CsI(Na)-PMT measurements.

4.2.3. Capture results

The prompt γ -ray energy spectra obtained for the two samples and two detectors are shown in Figs. 4.12 and 4.13 where their shapes are compared with the ENDFB-VII.1 evaluated library in for the $^{197}\text{Au}(n,\gamma)$ case. CENDL-3.1 evaluated library was used instead for the $^{nat}\text{Ag}(n,\gamma)$ case, since this material was not evaluated in the ENDFB-VII.1 library. The histogrammed energy spectra were corrected by the evaluated neutron flux corresponding to the 2011 campaign.

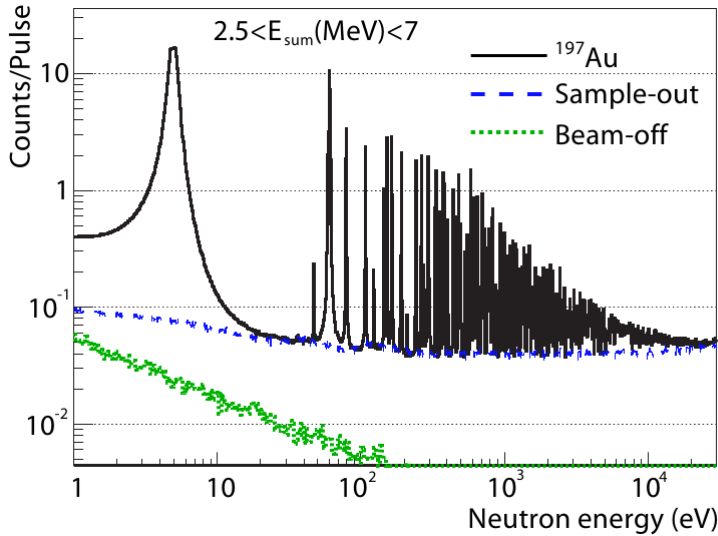


Figure 4.14.: Measured counting rate distributions corresponding to the ^{197}Au and the dedicated background measurements. Figure taken from Ref. [61].

A background contribution is observed at the lower region in every measurement. As shown in Fig. 4.14 (see Ref. [61]), the contribution is mainly due to the fact of the activity of different materials in the experimental area, because of the in-beam γ -rays 2.2 MeV from the $^1\text{H}(n,\gamma)$ reaction produced in the moderator material surrounding the spallation target, Ref. [71]. In any case, the rate between the resonances below 5 eV and the background contribution shows a neutron-capture reaction contri-

bution greater than the background. It is worth noting the green line in Fig. 4.14, showing how the beam-off noise raises at lower energies, because the lower energy bins correspond to the larger time bins.

For the sake of comparison of the measured spectra of both ^{197}Au and ^{nat}Ag with the above mentioned evaluated libraries, the evaluation cross sections were scaled to the maximum value obtained by the largest resonance of the measured spectra.

These capture measurements allowed to tune-up the scintillator's setup, and its results confirm that the radiation detectors and the analysis techniques used in this work are suited to measure the prompt γ -rays emitted from (n,γ) reactions, even in a noisy environment.

4.3. Prompt γ -rays from $U5(n,f)$ reaction

A better understanding of the fission process and a continuous development of nuclear technologies demands a detailed and precise study of the fission processes, mainly the yield of fission fragments, FF, and both the neutrons and the γ -rays emitted during the fission process. The deeper study of the neutron emission during the fission process encourages, however, the study of the prompt γ -rays that implies uncertainties on the nuclear data needed for the design of new fast reactors. For example, the local heating can be mispredicted by up to 30% even in well known power reactors [72].

After the capture measurements in this work, some tentative measurements were done on the $^{235}\text{U}(n,f)$ reaction, where an important portion of the energy released, around 7%, is due to the prompt γ -rays. The request of a better characterisation of the prompt fission γ -yields have been formulated in the Nuclear Data High Priority Request List of the Nuclear Energy Agency, since the required accuracy, a 7.5% [73], was not achieved in previous measurements done in the 1970's [74, 75].

4.3.1. Experimental setup

During the 2012 campaign, the CeBr_3 -PMT and the $\text{CsI}(\text{Na})$ -PMT detectors, already described in the previous chapters, were placed in parallel

to the PPAC detectors (above described in Section 4.1), using the configuration showed in Fig. 4.15. The two scintillator detectors stood at 39 cm from the centre of the ^{235}U target in between of PPAC 7 and PPAC 8 (see Fig. 4.16 (a)), in order to get measured the prompt γ -rays resulting from the fission process, in coincidence with the PPAC pulses, that show to be faster than those from the scintillators, as it is noticeable in Fig. 4.8. Thus, a method for coincidences, based on a specific trigger routine, has been developed. The main goal was observing the γ -rays from the resonances at low neutron energies.

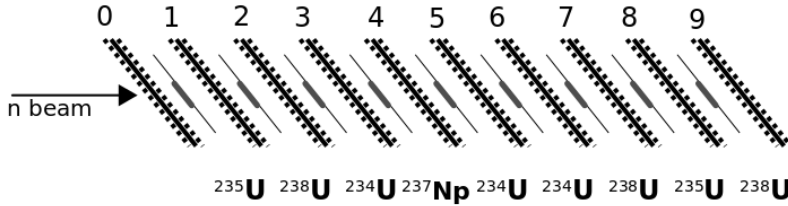
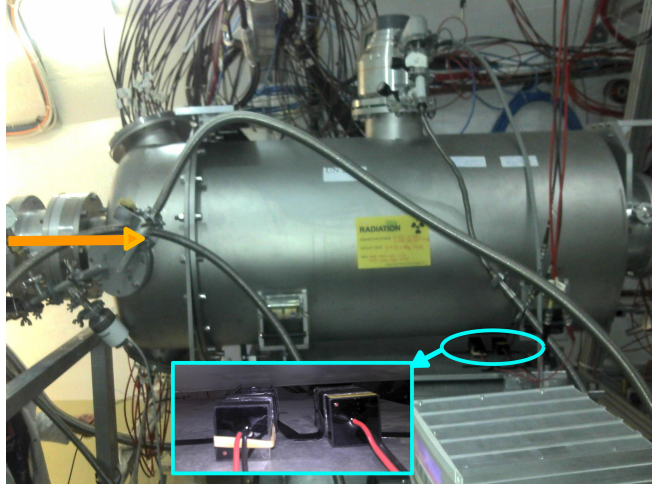


Figure 4.15.: Top view of experimental setup of the PPAC chamber: ten PPAC detectors and 9 nine targets. The PPAC detectors and the targets were tilted 45° around the vertical axis.

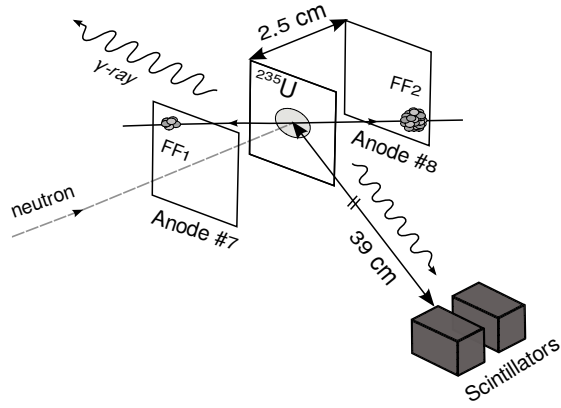
Nine targets and ten PPACs are contained in the same gas-tight enclosure and so the challenge was to identify the origin of each fission event, with its corresponding time stamp. The way to identify each fission event and the prompt γ -rays was based on the coincidence method to be detailed in the following sections. Two different studies were performed: on the one hand, the study of time signal coincidences between the CeBr_3 -PMT and the PPAC anodes 7 and 8 and on the other hand, the study of the coincidences between the $\text{CsI}(\text{Na})$ -PMT and the anodes 7 and 8. In Fig.4.16 (b), a schematic view of a coincidence between anode 7 and 8 and a scintillator is shown.

4.3.2. Data analysis

Coincidence trigger Firstly, the coincidence trigger used for such purpose is here explained. In order to get the coincident measurements between both detectors, an algorithm was created that identifies all possible



(a)



(b)

Figure 4.16.: Experimental setup of the PPAC chamber and the scintillators detectors. The orange arrow indicates the neutron beam (a). A schematic view of an event giving coincident signals between anodes 7 and 8 and a scintillator (not in scale) (b).

simultaneous signals. The main idea was to use binary sequences being identified with each PPAC anode and scintillator detector. That simplifies later the analysis, choosing any coincidence condition just by applying a simple binary mask. For example, when wanted to identify coincident signals between PPAC #8 and the scintillator, the condition (mask) applied to the bit sequence would be as follows: `if( num & (1<<8) == 1 )`. The logical `&` bitwise AND operator checks for the value of the eighth bit stored in `num`, that is the bit sequence created to tag the signals and store them as an integer value. In case of multi-coincidence events, more complex structures can be required. For instance, the coincidence between the crystal, and the 7th and 8th PPAC anodes can be expressed as follows:

$$\text{if } (num \& (1 << 8) == 1 \&\& num \& (1 << 7) == 1), \quad (4.6)$$

or even simpler:

$$\text{if } (num \& (1 << 8 + 1 << 7) == 1). \quad (4.7)$$

Furthermore, where anti-coincidence with other detectors are relevant, it can be easily selected by asking the specific bits to be explicitly zero.

The code works as follows, first, the measured times and the trees containing data from different detectors are synchronised. Then, the algorithm loops over the sorted by time events and in case it finds two concurrent signals within a time window, detailed above, it stores the time, the corresponding neutron energy, the velocity and other useful information as the amplitude, area and width of the signal for further analysis. The identification number of the PPAC detector is stored into a binary list for that event as true. Then a subsequent loop is done over the remaining detectors in order to identify other possible positive signals. These coincident measurements are added to the binary list as true values as well, conforming the final value of `num` to be stored in the tree. In parallel, also all the coincidence signals between the PPAC detectors are stored into another binary array. The schematic algorithm design is shown in Fig.4.19.

Windows selection Firstly, the detectors were time calibrated and synchronised, using the same method as in the previous neutron capture section was used for both scintillator detector: the digital filters there used,

and the γ -flash time taken as a time-of-flight reference. Similarly, the PPAC signals, already filtered and stored in a ROOT Tree, were indexed to the first signal registered by each anode, mostly corresponding to the γ -flash signal.

$$TOF_{detector} = t_{signal} - t_{\gamma-flash} + 620 \text{ (ns)} \quad (4.8)$$

To search a coincident event, two time windows were defined: the first one, W_1 , related to the difference between the time-of-flight of the scintillator detector, t_{Scin} and the time-of-flight registered by an anode of a PPAC:

$$|t_{Scin} - t_{Anode}| < W_1 \text{ (ns)} \quad (4.9)$$

Once the coincidence was found, a new coincidence search, W_2 , between the time-of-flight of the signal anode previously found and the time-of-flight of a new signal anode different from the previous one, (the coincidence trigger explained avoid the repetition of the already registered event):

$$|t_{Anode_i} - t_{Anode_j}| < W_2 \text{ (ns) where } i, j \in [0, 9] \text{ and } i \neq j \quad (4.10)$$

The here used time window $W_2 = 12 \text{ ns}$ was obtained in a previous work [76].

An iterative study of the time window, W_1 , for both scintillators were carried out to characterise the coincidence events. The time windows, W_1 , chosen for the study were symmetrical. The number of coincidences registered by the scintillators within the window were plotted for each W_1 value studied, as shown in Fig. 4.17. In both figures, one for the $CeBr_3$ -PMT (a) other for the $CsI(Na)$ -PMT (b), two trends are observed, being flatter at wider W_1 , meaning that background events were registered as prompt γ -rays, therefore, such events were discarded for the further analysis.

Once it was proven the efficient detection of coincident events, the time window W_1 for each scintillator was widely opened in order to characterise

4. Beam-tests in the n_TOF experiment

the time difference distribution between the PPAC anodes and the scintillators. Fig. 4.20 shows the result of the calculation of the difference between the t_{Scin} and the averaged of the t_{Anode7} and t_{Anode8} , finding the coincidences time dispersion, the background contribution and the residual time offset. The residual time offsets corresponds to a walk effect of the signals, that was corrected. In the CeBr₃-PMT case, Fig. 4.20 (a), it is observed a time distribution of the coincidences in which there is little appreciation of the background contribution. Hence, a $W_1 = 50$ ns (-25 to 25 ns) was chosen for the CeBr₃-PMT detector. In the CsI(Na)-PMT case, Fig. 4.20 (b), it is observed a broader time distribution; a $W_1 = 80$ ns (-40 to 40 ns) was chosen. Once the study was performed, the events were selected by the time parameters previously obtained. In addition to the time conditions, a condition related to the lower amplitude PPAC anodes 7 and 8 signals was included in order to reject the background produced by the α emission of the radioactive targets.

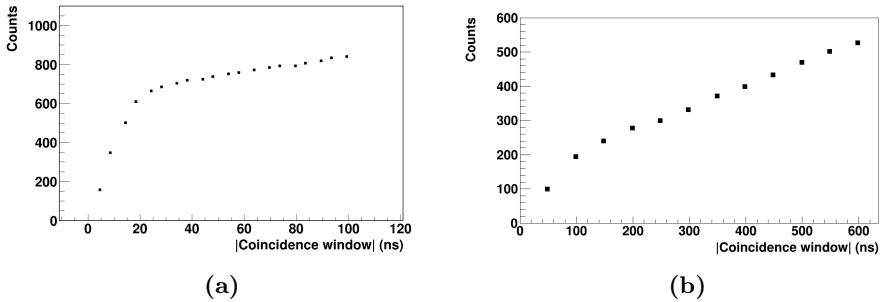


Figure 4.17.: Study of the W_1 (coincidence window) for the CeBr₃-PMT (a) and the CsI(Na)-PMT (b). The statistics for each time window is shown. Two contributions are observed.

The neutron energy for each coincidence was calculated and was corrected by the neutron flux corresponding to the 2011 campaign. The data obtained were compared to the evaluated function of the $^{235}\text{U}(n,f)$ cross-section from ENDF/B-VII.1 library (Fig. 4.21) which was scaled to the maximum value of obtained by the largest resonance of the measured spectra for the sake of comparison. Even though the low statistics gotten, because of the very reduced beam time available, the good results con-

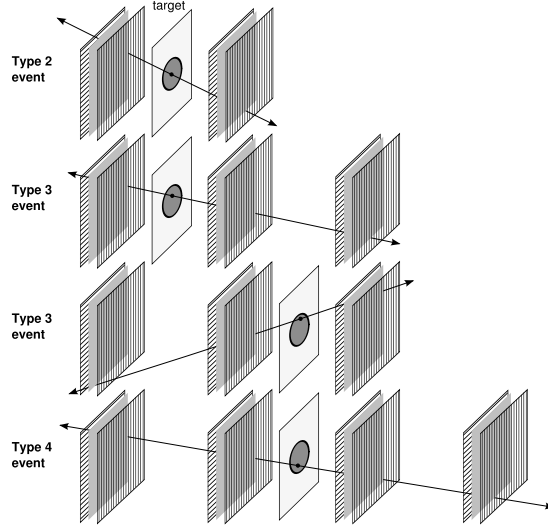


Figure 4.18.: Types of events that happen in PPACs detectors. Type 3 and 4 must be removed from the analysis to avoid the distorted measurements [77].

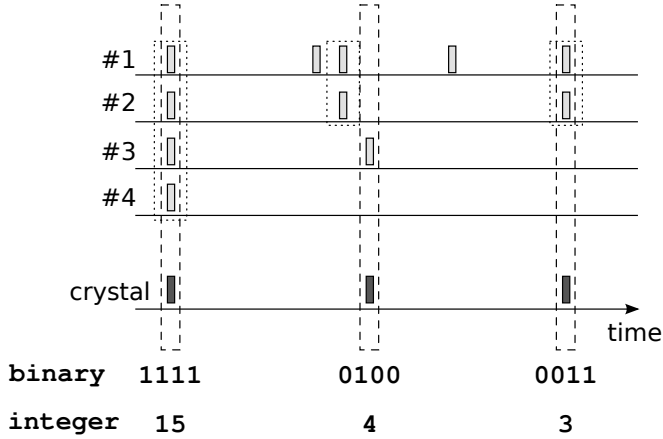


Figure 4.19.: Schematic representation of the coincidence algorithm. The dashed lines represent coincident signals between the crystal and the PPAC detectors. The dotted lines show the coincidence among PPACs. Each coincident measurement is stored using a specific integer number. This value later can be used to select via a binary mask one specific coincidence condition [77].

4. Beam-tests in the n_TOF experiment

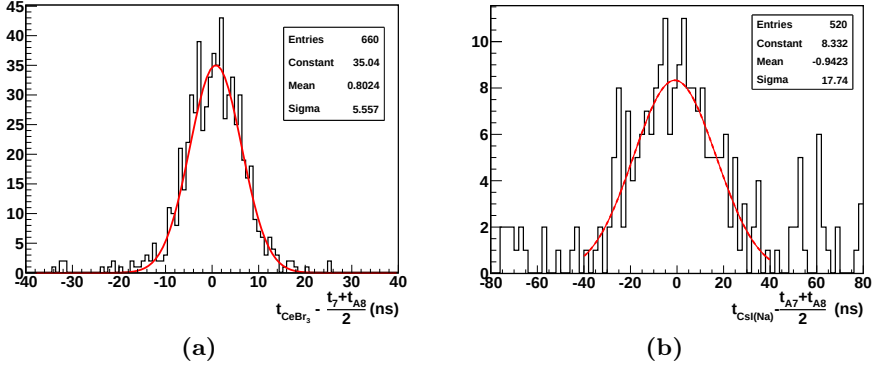


Figure 4.20.: Distribution of the time differences between the average time of the anodes 7 and 8 and a scintillator detector: CeBr₃-PMT (a) and CsI(Na)-PMT (b).

firm that the spectra can be measured using these kind of small and fast scintillator detectors. The promising results, even though very preliminary, allow to keep open the way to further experiments aiming to cope with the requests of deeper understanding of the prompt- γ produced along the fission process.

4.3. Prompt γ -rays from $U5(n,f)$ reaction

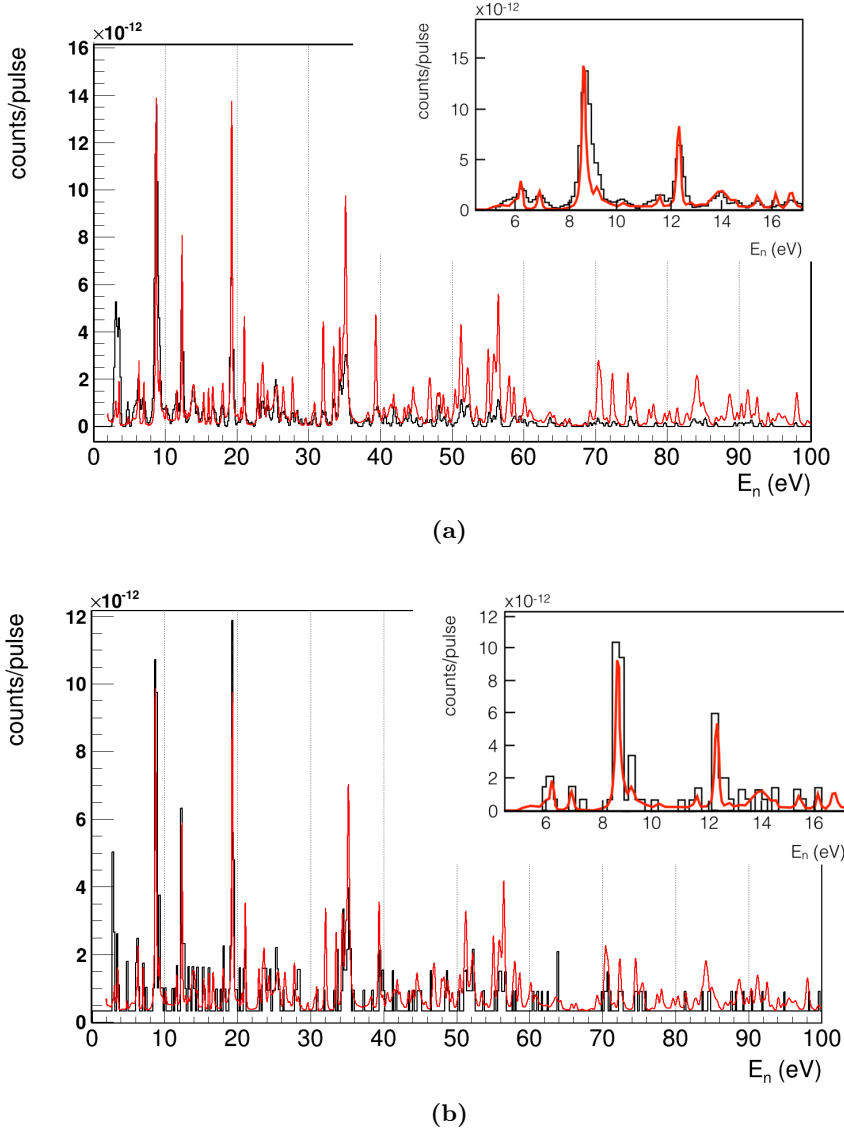


Figure 4.21.: Black line: Measured counting rate distribution corresponding to the $^{235}\text{U}(n,f)$ reaction. The data were corrected by the evaluated neutron flux. Red line: ENDF/B-VII.1 cross section evaluation scaled to the measured data for comparison. (a) corresponds to CeBr₃-PMT measurements, (b) corresponds to CsI(Na)-PMT measurements.

Fissionless γ -ray emission When analysing the coincidences for the $^{235}\text{U}(n,f)$ reaction, a high quantity of events are also detected besides the coincident events. For the $\text{CeBr}_3\text{-PMT}$ detector, a dataset has been recorded excluding the events tagged as fissions is shown in the upper panel histogram in Fig. 4.22, where a clear resonant signal is observed above the background. This background was characterised in the previous prompt γ -rays from capture measurements and can be removed using a potential fitting function ($y = A \times E_n^B$). Once it is removed, the contribution clearest observed corresponds to a resonance at $E_n \simeq 5.17$ eV (see Fig.4.22 lower panel). Coming from the other targets placed in between their corresponding PPAC detectors. Finally, it was concluded that this contribution comes from the $^{234}\text{U}(n,\gamma)$ reaction, whose cross section shows a large resonance at that energy, having a very huge peak value of 22277.7 barns, according to the ENDF/B-VII.1 evaluation library. It is noteworthy how a such big capture resonance produces only a small signal in the fission-related γ -ray spectra shown in Figs. 4.21.

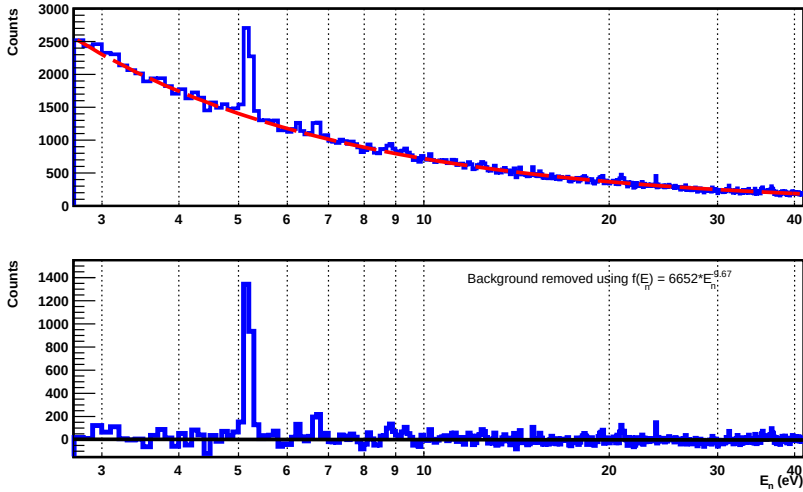


Figure 4.22.: Top panel: events detected by the $\text{CeBr}_3\text{-PMT}$ detector versus neutron energy when excluded the fission coincidences. The background was fitted to a potential function. Bottom panel: Events detected subtracting the potential background. The peak (resonance) came from the $^{234}\text{U}(n,\gamma)$ reaction.

4.4. γ -flash study

What γ -flash means? During the spallation process, when protons of 20 GeV impinge on the lead target, besides neutrons, a huge amount of γ radiation and both neutral and charged particles are produced as result of the hadronic cascade developed at the very beginning of the process. Besides the big amount of neutrons, these spallation products travel along the beam lines interacting with their components and so producing new radiation and particles that disturb the neutron beam produced. In spite of the elements placed in both beam lines, such as sweeping magnets and collimators, some of this products, mostly γ -rays and electron-positron pairs produced only at the end by them, arrives to the experimental areas. At n_TOF experiment, the contribution of these particles and radiation to the detectors placed in the experimental areas is an inconvenient, since it *blinds* the detectors used for an specific lapse of time preventing so to measure the reactions produced by the most energetic neutrons released during the spallation process. The blindness time will depend on the detector nature, their electronics and on the fact of being in-beam or out-of-beam. In Fig. 4.23 the signal produced by the γ -flash is showed for different detectors used at n_TOF. The first arriving signal corresponds ever to the γ -flash and due to this fact, the γ -flash is taken as a time reference for the time of flight of the subsequent neutron reactions detected and then recorded by the data acquisition system.

Regarding deeply the γ -rays effect evolution and taking into account the information given by different detectors, both in-beam and out-of-beam, two components were differentiated in Refs. [55, 78]: prompt, before TOF $< 1 \mu\text{s}$, mainly formed by γ -rays produced during the spallation process and delayed, after TOF $> 1 \mu\text{s}$, formed by γ -rays from radiative neutron capture reactions occurring in both the moderator and the cooling system as well as from material surrounding the spallation target. This Section focus on the TOF $< 1 \mu\text{s}$ component and three different components were differentiated within that range, as it will be explain later.

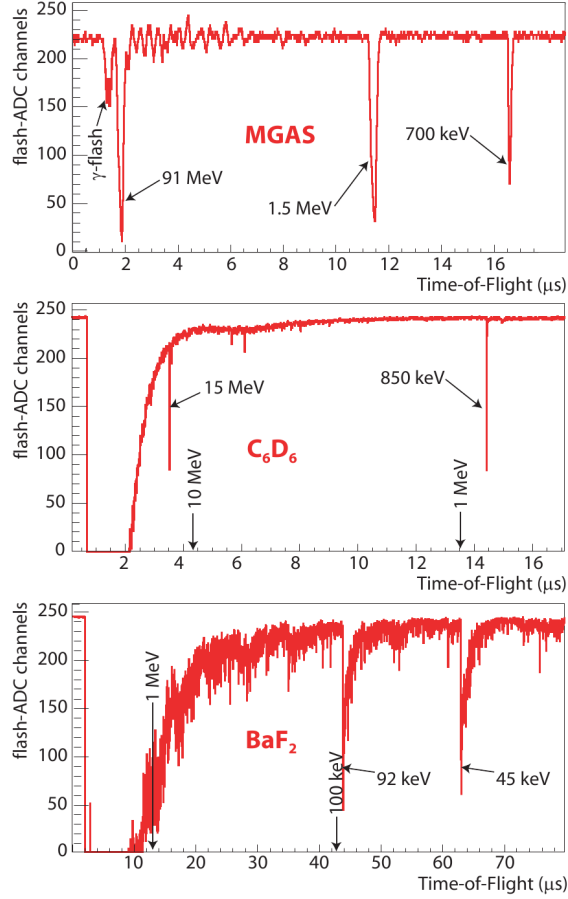


Figure 4.23.: γ -flash signals produced in three n_TOF detectors. Top panel: MicroMegas (a gaseous detector). Middle panel: C_6D_6 (a liquid scintillator detector). Bottom panel: BaF_2 (a crystal scintillator detector). The values in the figures corresponding to neutron energies are given for guidance.

4.4.1. γ -flash measurements at EAR1

In order to understand the behaviour and origin of the γ -flash, the CeBr_3 -PMT, $\text{CsI}(\text{Na})$ -PMT, LaBr_3 coupled to a PMT, and plastic scintillator detectors were used to measure this effect out of the beam, in addition to other n_TOF detectors such as PPACs and CVD diamond detector giving information on the in-beam contents.

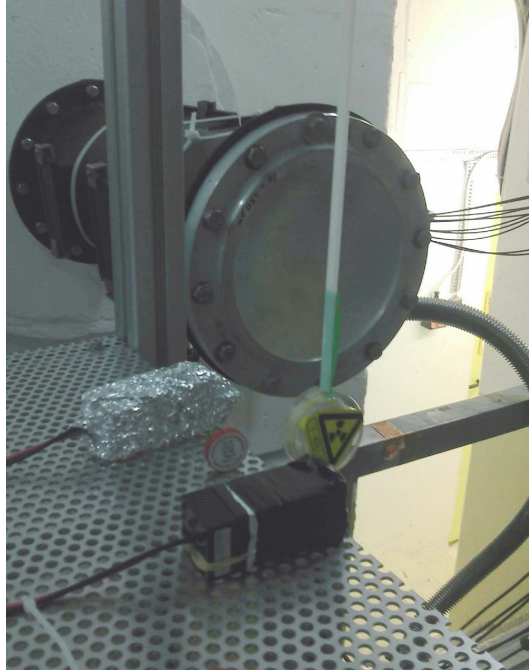


Figure 4.24.: CeBr_3 -PMT and $\text{CsI}(\text{Na})$ -PMT detectors placed at EAR1 out of beam for γ -flash measurements.

To characterise the effect of γ -flash outside the beam, the CeBr_3 -PMT was placed as in the Fig. 4.24 and a set of γ -flash signals so acquired are shown in Fig. 4.25. The γ -flash pulse shape-structures are different from bunch to bunch of protons, leading to assume that the γ -flash is mainly formed by a set of individual γ -rays escorted by electron-positron pairs and other kind of photons and electrons by them produced. Some of those γ -rays reach the EAR1 so fast that the scintillators are not able

to resolve it, so producing a wider pulse. Since the scintillator was placed out of beam and it is supposed that most of the γ -rays from the spallation process comes from the vacuum pipe, the fact that the signals differ from event-to-event suggests a complex statistical time distribution, as if that the detected photons and charged particles were coming from in-beam γ -rays interacting with the materials they are passing-through, such as the aluminium windows or aluminium pipes. A few signals produced by a $\text{LaBr}_3(\text{Ce})$ ¹ scintillator detector is also shown in Fig. 4.26. The signals also differ from event-to-event as it was observed in the CeBr_3 case. It must be noted that the decay time of $\text{LaBr}_3(\text{Ce})$ crystal, typically 16 ns, is faster than the one of CeBr_3 but, however, this is not observed in the pulse shapes in Fig. 4.26, where the $\text{LaBr}_3:\text{Ce}$ crystal pulses are wider, and, besides this, more pile-up is observed, because the volume of a $2'' \times 2'' \phi$ cylinder, being 12.3 times bigger than the CeBr_3 one, increases so the number of detected γ -rays. Consequently, the reduced volume of the CeBr_3 permits to distinguish more accurately the signals produced by the γ -flash.

From a thorough observation of the raw pulses of the CeBr_3 -PMT detector in Fig. 4.25, it can be seen that its width is wider than the registered signal produced by individual γ -rays from a radioactive source, and, moreover, their structure differs from bunch to bunch of protons because pile-up is commonly observed.

On the other hand, a fraction of the pulses becomes larger, in terms of amplitude, than the dynamic range of the DAQ system so creating a saturation problem. Concerning the energy deposited, it is not easy to provide a value since we were dealing with the pile-up of the many pulses related with the γ -flash, as above mentioned, but, nonetheless, in Fig. 4.27 is shown a not so high γ -flash pulse to be compared to the signal produced by a 1836 keV γ -ray from ^{88}Y . Assuming a linear detector response in terms of energy, as it was proven in Chapter 3, the deposited energy by the γ -flash would be larger, in this case, than 10 MeV.

In Fig. 4.28, the γ -flash pulses produced in PPAC, CeBr_3 -PMT and $\text{CsI}(\text{Na})$ -PMT detectors followed by pulses from neutron induced reactions are shown. In (b) and (c) the neutron energy values in the figure are given for guidance. The PPAC detector detects the most energetic reactions after

¹from the Grupo de Innovación Nuclear from CIEMAT, Spain.

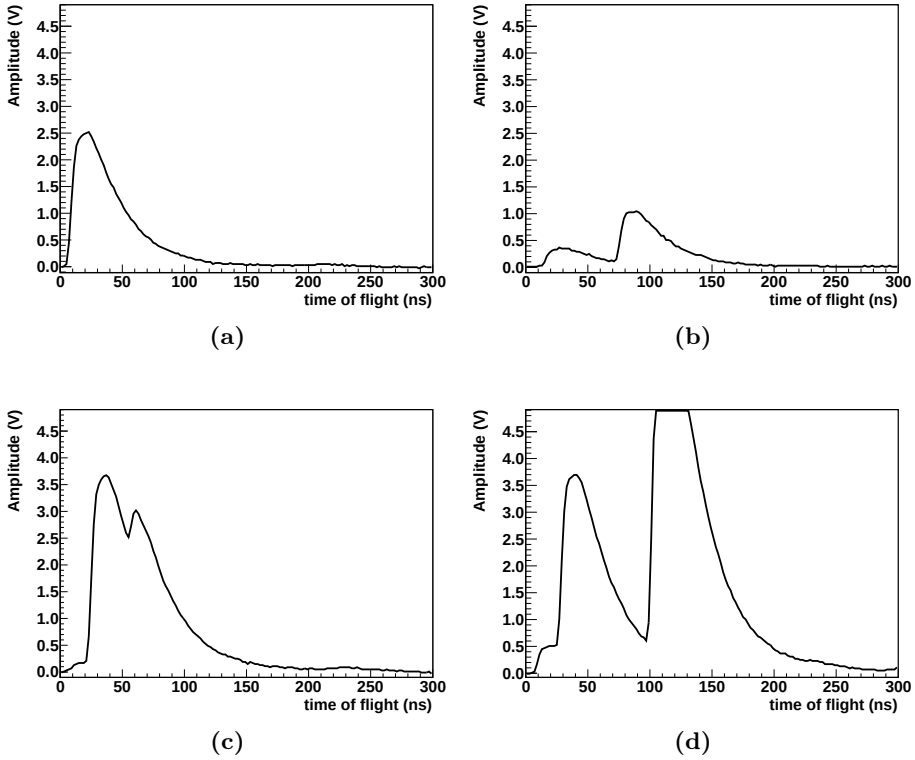


Figure 4.25.: γ -flash pulses from CeBr₃-PMT out of beam during the 2012 detectors test.

4. Beam-tests in the n_TOF experiment

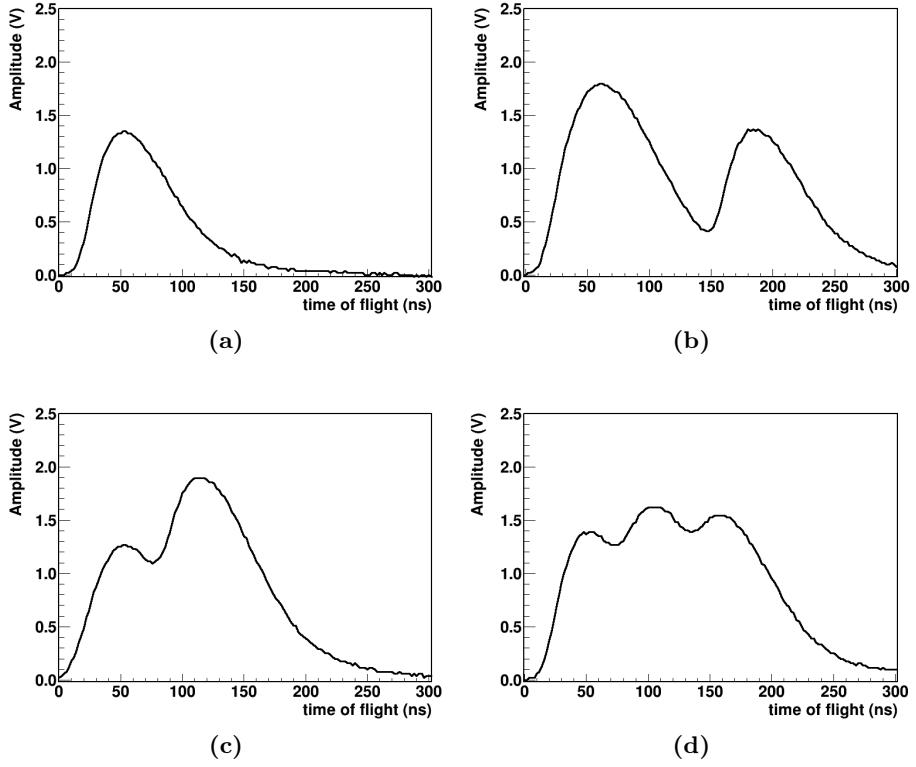


Figure 4.26.: γ -flash pulses from $\text{LaBr}_3\text{:Ce}$ during the 2012 detectors test for γ -flash.

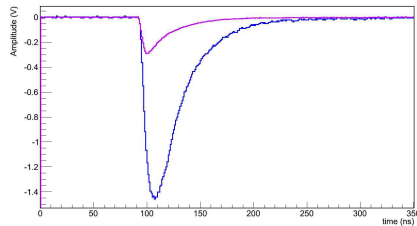


Figure 4.27.: γ -flash pulses (in blue) compared with 1836 keV pulses from an ^{88}Y γ -ray source.

the γ -flash. In (d), a coincidence event from $^{235}\text{U}(\text{n},\text{f})$ reaction between a CeBr_3 -PMT signal and Anode 7 and 8 is shown for comparison.

As previously mentioned, two diameters of the second collimator are used at EAR1, respectively, for the capture and fission measurement. Comparing the results gotten when using both diameters it can be drawn out the correlation of the collimator diameter with the γ -flash effect intensity. Figs. 4.29 (a) and (b) are showing for the fission measurements (80 mm ϕ), that the γ -flash signals for both CeBr_3 -PMT and $\text{CsI}(\text{Na})$ -PMT were strongly saturated. Moreover, in the $\text{CsI}(\text{Na})$ -PMT case, a rebound is observed after the decay time of the pulses which is not observed in the non-saturated pulses, see Fig. 4.29 (c). In order to overcome this problem, a signal attenuator has been designed. A more detailed description of this design was given in Chapter 1. The effectiveness of such attenuator can be observed in Fig. 4.29 (d), where the saturation problems and the rebound are not appreciated in the attenuated signals, solving so those problems. So, finally can be deduced that the larger the diameter of the second collimator, the larger is the amplitude of the γ -flash signals detected out-beam by CeBr_3 -PMT, demonstrating the pile-up effect.

Lead filters in-beam

To blank out different neutron energies from the beam, a neutron-filters box is installed in the beam-line 1 (see Fig. 4.4) , being possible to combine different filters. For the γ -flash study, two lead filters of 1 cm and 2 cm thickness were used in order to attenuate the in-beam photons. Four configurations were so performed: no filter in beam, 1 cm, 2 cm and 3 cm. The analysis of these configuration consisted of counting the number of the saturated γ -flash pulses (pulses that exceed the DAQ amplitude range) for each configuration. All the γ -flash pulses here studied were produced by dedicated (maximum intensity) proton bunches from the PS. When no filter was set in beam, most of the γ -flash pulses detected by the CeBr_3 -PMT were saturated (77 %). When the lead filters were used the number of saturated pulses was reduced as the thickness increased: from 47 % for 1 cm and 31 % for 2 cm, down to 22 % for the 3 cm filter. It is worth adding too a comment on the number of signals produced by the γ -flash that were either not detected by the CeBr_3 -PMT or having a pulse height

4. Beam-tests in the n_TOF experiment

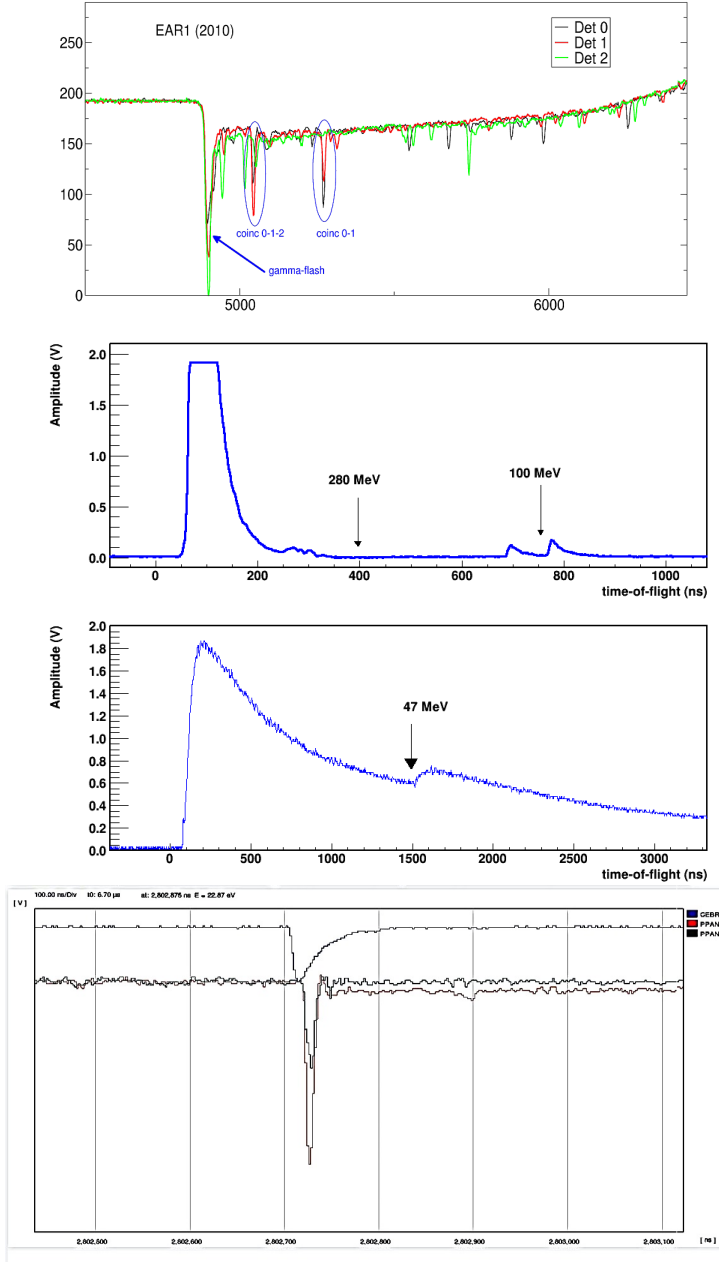


Figure 4.28.: (Top panel) γ -flash pulses from different PPAC anodes (Second panel), CeBr₃-PMT detector and (Third panel) CsI(Na)-PMT detector. In the bottom panel a coincidence between a CeBr₃-PMT signal and Anode 7 and 8. Neutron energy values are given for guidance.

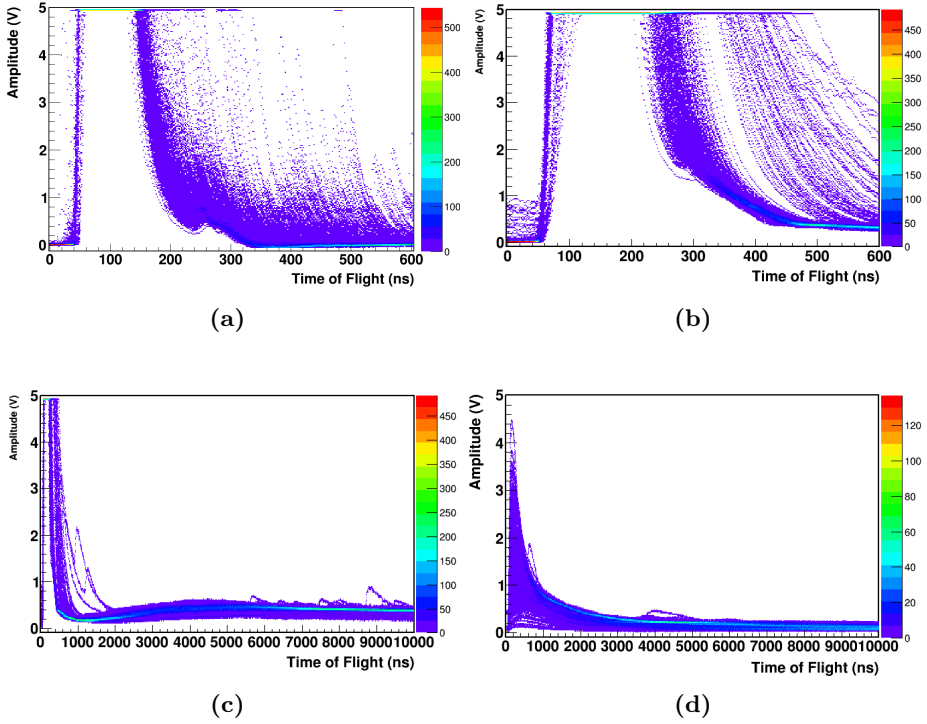


Figure 4.29.: γ -flash pulses from CeBr₃-PMT (a) and CsI(Na)-PMT (b) during the 2012 PPAC fission measurements for γ -flash. In (c), the CsI(Na)-PMT γ -flash signals in a wider range. Note the rebound after the decay time of the saturated signals. In (d), γ -flash attenuated pulses from CsI(Na)-PMT using a Zener diode based attenuator (d). Note that the rebound after the decay time of signals was removed.

not exceeding the threshold set in the DAQ system. These numbers are also related with the lead filter thickness: 15 % for no filter, 15 % for 1 cm Pb filter, 35 % for 2 cm and 47 % for 3 cm. It can be concluded that setting thick lead filters in the beam produces a severe reduction of the γ -flash, reinforcing the idea of the principal role of the very-high energy gammas coming from the spallation target through the beam pipe.

PPAC detectors

PPAC detectors in-beam have a very low γ -ray detection efficiency, but the γ -flash is detected by the PPACs. Keeping the main hypothesis of a γ -flash originated from primary γ -rays, the interaction of such γ -rays with the aluminium windows as well as with the PPACs materials leads to its conversion in energetic and forward peaked charged pairs, that PPACs can detect. The pulse shape of the γ -flash detected by the PPACs was obtained by averaging a number of pulses registered by one anode, as shown in Fig. 4.30 (a). Note that the pulse shape produced by the γ -flash did not differ significantly from event-to-event, but its amplitude is well correlated with the intensity of the proton bunch on the spallation target, as shown in Fig. 4.31², leading to a linear dependence of both observables and to conclude, that the signal produced in the γ -flash in the EAR1 by the PPAC anodes, is larger as the intensity of the proton pulse increases. Due to the short width of the PPACs signals, of around 10 ns, a study of the time structure of the γ -flash has been performed. In Fig. 4.30 (b), is the temporal distribution of the first-arriving pulses as well as the second-arriving signals from an anode. Taking into account a lack of resolution of 10 ns in the pulse shape analysis routine, it can be seen how that the first-arriving ones are stacked-on in the firsts 5 ns, whereas the second-ones arrives spread over a range from the end of the first-arriving pulses up to some 100 ns. It is worth mentioning that these pulses that in the PPACs are detected as first and second arriving are not resolved by scintillation crystals that have much broad decay times, but it can be detected too by the CVD diamond detector.

²the information of the proton beam is given by the Beam Current Transformer (BCT) monitor proton intensity sent to the target and the Wall Current Monitor (WCM) provides a pulse (called pick-up signal) related to the proton beam intensity

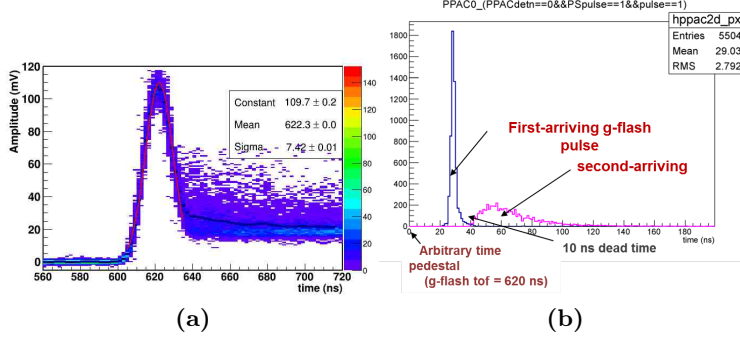


Figure 4.30.: Fig. (a) shows the average pulse of the γ -flash registered by an anode of a PPAC for dedicated PS pulses. Note the width of the pulse: 18 ns. Fig. (b) shows the time distribution for the γ -flash pulse. The first-arriving pulses were peak distributed in a range of 5 ns (blue line) whereas the second-arriving pulses were broader for 60 ns (pink line) [79].

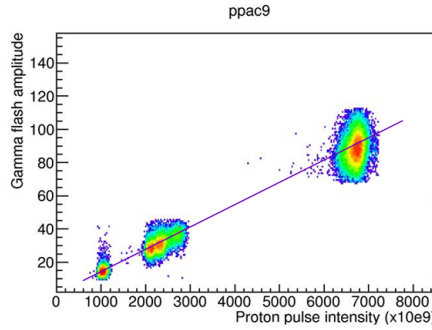


Figure 4.31.: γ -flash amplitude in the anode 9 in the PPAC detector as a function of the the proton pulse intensity. Note the linear relation between the parasitic (less than $3 \cdot 10^{12}$) and dedicated proton pulses [79].

CVD diamond detector

The CVD diamond detector is a very fast solid-stated detector from Technische Univesität Wien, TUW, Austria. The in-beam and low γ -rays efficiency detector have been tested in both experimental areas. The γ -flash signals, shown in Fig. 4.32, were averaged as in the previous cases. It is noteworthy that the 16 ns FWHM of the averaged signal, fitted to a 2nd order polynomial function, corresponds to the first-arriving signals convoluted with the 7 ns spread related to the width of the bunch of protons that impinges on the spallation target. The second-arriving pulses are also detected, more scarcely and spread along the following tenths of ns.

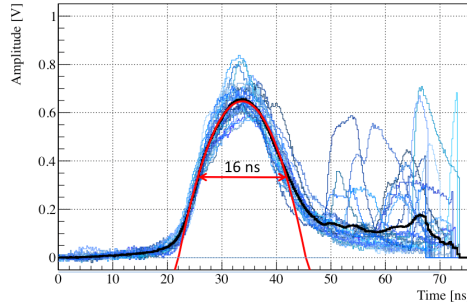


Figure 4.32.: γ -flash signals from CVD Diamond detector acquired in EAR1 [80].

CeBr₃-PMT and plastic scintillator detectors

As a result of the different shape of the pulses produced event-by-event by the γ -flash in the CeBr₃-PMT as well as in the plastic scintillator detectors, a ROOT script has been written in order to get the averaged profile of different set of signals, in order to obtain information about the structure of the detected signals.

From measurements carried out in the EAR1, in the 2012 campaign, it is observed that the γ -flash average profile for CeBr₃-PMT is wider than a γ -ray emitted by a radioactive source and registered by the detector (Fig. 4.33 (a)). Similarly, a study was performed in a later campaign,

in 2014 commissioning, where the averaged profile resulted narrower than in the former campaign. Before the 2014 commissioning campaign, some shielding improvements were performed at the beam entrance in EAR1; for instance, the diameter of the pipe that crosses the concrete wall was reduced from 20 to 10 cm and the space between the outer of the pipe and the wall was filled by surrounding iron cylinders. The narrower average profile obtained for the 2014 campaign (Fig. 4.33 (b)) leads to conclude that the improvements of the shielding led to a lower contribution of the γ -flash signals.

The plastic scintillator detector here used has been previously described as it was used for the cosmic-rays measurements performed in Chapter 3. It was placed in the EAR1 in order to detect the γ -flash in the 2014 commissioning campaign. As it was previously mentioned, its low detection efficiency for γ -rays, due to its 0.5 mm thickness, permits to find out the contribution of charged particles to the signal produced by the γ -flash. In Fig. 4.33 (c), the plastic's averaged profile is shown, compared to the signal produced by a single MIP (red line). As it was observed in the case of the CeBr₃-PMT measurements, the γ -flash averaged profile is here also wider than the signal produced in the case of single charged MIPs (cosmic-rays μ 's in this particular case).

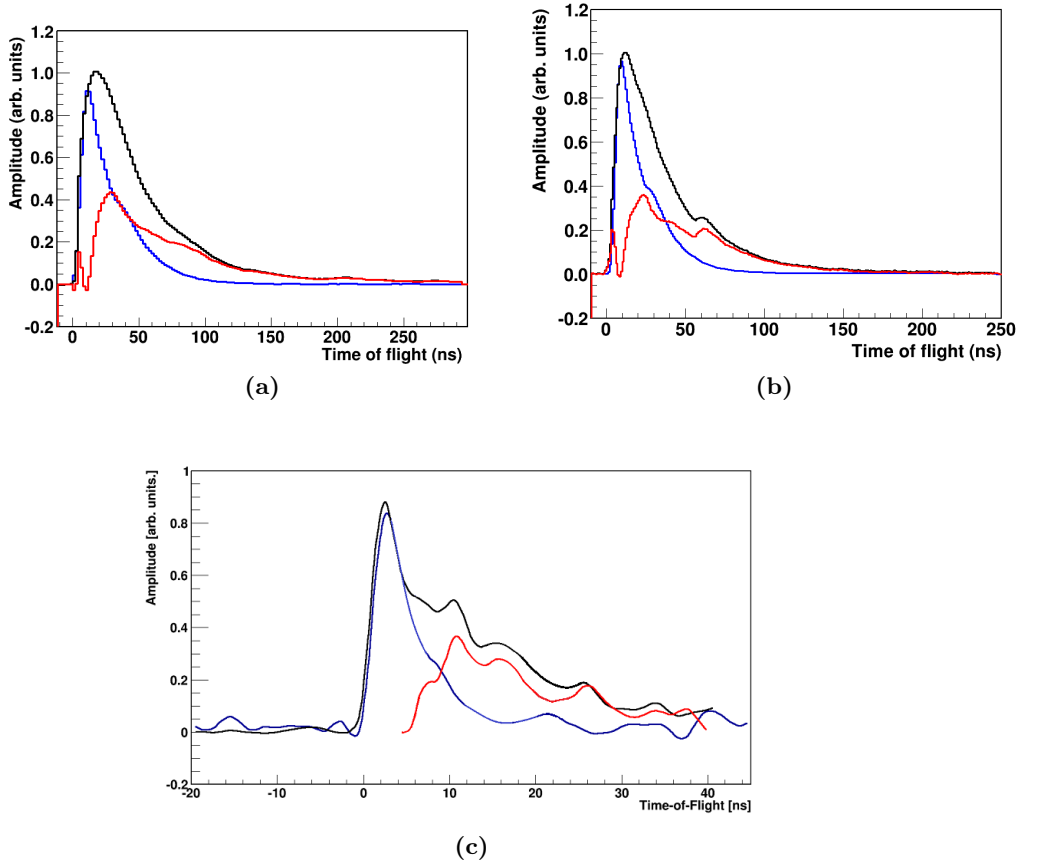


Figure 4.33.: Average pulse (black line) of the γ -flash measured using CeBr₃-PMT detector for EAR1 in 2012 (a) and in 2014 (b) after an upgrading of the area shielding. Blue line corresponds to the average pulse of γ -rays coming from a radioactive source (^{137}Cs). In (c), the γ -flash plastic average pulse (black line) is compared with a cosmic-ray muon pulse (blue line). The subtraction of both corresponds to the red line.

4.4.2. γ -flash measurements at EAR2

In EAR2, the time of flight resolution is worsened due to the shorter beam line in comparison with the EAR1. The CeBr_3 -PMT and the plastic scintillator measured the γ -flash during the 2014 campaign in EAR2. The set-up of such measurements is shown in Fig.4.34. The averaged profile for the γ -flash detected by the CeBr_3 -PMT is shown in Fig.4.35 (a). In spite of the pile-up that is observed in the first 250 ns of time of flight, two contribution can be distinguished: the larger one, after 30 ns, was fitted to a gaussian plus an exponential function and then subtracted from the original in order to show up the smaller contribution of the γ -flash very-prompt component. A similar behaviour is observed in the plastic scintillator pulses, as can be seen in Fig.4.35 (b), when the same fitting procedure were performed.

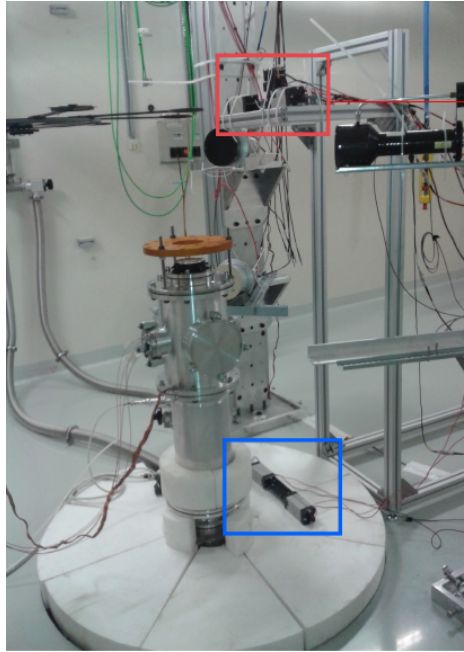


Figure 4.34.: Setup for γ -flash in EAR2. The CeBr_3 -PMT and the plastic scintillator were placed close to neutron beam coming up from the bottom (red square).

PPACs and CVD diamond detectors

Concerning the PPACs, a new reaction chamber containing two targets and three PPACs [81] measured the γ -flash-related signals in this area. A γ -flash signal in EAR2 is shown in Fig. 4.36. Where the very-prompt component of the γ -flash signals is barely appreciated.

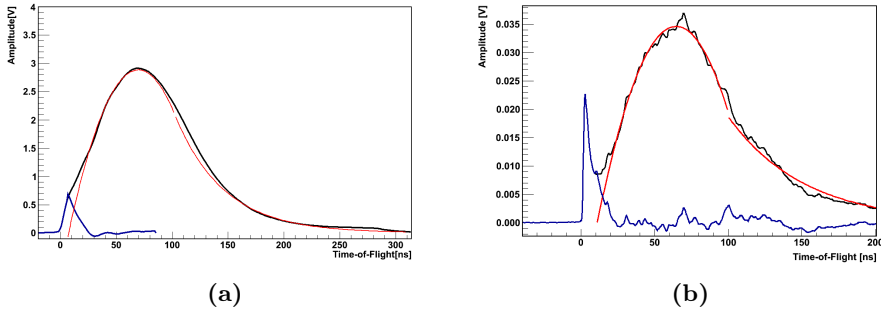


Figure 4.35.: Averaged pulse (black line) of the γ -flash measured using CeBr₃-PMT detector (a) in EAR2. After 20 ns was fitted to a gaussian plus an exponential functions (red line). Blue line corresponds to the subtraction of such fitting. The same procedure was used for the average pulse of the plastic scintillator detector (b).

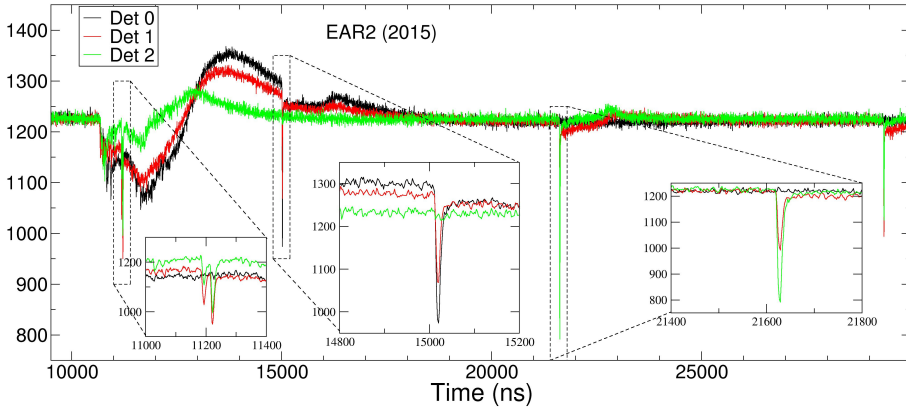


Figure 4.36.: γ -flash signal from PPAC detector acquired in EAR2.

As in the previous cases, the γ -flash signals detected by the CVD diamond detector in the EAR2 have been compared with the ones coming from the PPACs and from the fast plastic-scintillator. The summed-up signal can be seen in Fig. 4.37, showing the small contribution of the very-prompt γ -flash components, followed by a tail of escorting pulses. It is worth noting that this ultra-fast detector does not show dead time as the PPACs signal analysis produces, decently resolving the second-arriving pulses, conversely to the longer tailed crystals. The 16 ns produced by the stack of first arriving signals correspond to the width of the bunch of protons than impinges on the spallation target.

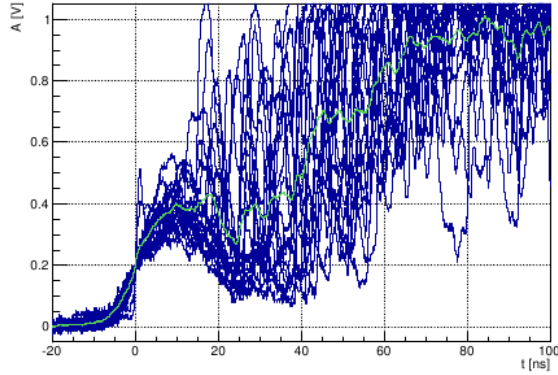


Figure 4.37.: γ -flash signals from CVD Diamond detector acquired in EAR2. [80]

4.4.3. γ -rays simulation

The γ -ray production during the spallation process and their transport through both beam lines going to the EARs, has been simulated by the n_TOF collaboration using the GEANT4 simulation tool-kit; the details on the simulation performances can be found in Ref. [78]. In this work are presented the result of such simulation by sorting the photons that arrive at both EARs in different regions in terms of energy and time.

The time interval concerning the γ -flash-related signals is considered in

the first μs . Then, it is subdivided in three smaller intervals: the first 1 ns (this very-prompt interval can be considered in the simulation, because here there is not incertitude in the t_0), from 1 ns to 100 ns (prompt) and from 100 ns to $1\mu\text{s}$ (delayed). These three components originate from the very prompt γ -rays emitted in high-energy interactions during the spallation process that actually span over around 7 ns, due to the length of the proton bunches. In Fig. 4.38 the analysis of the γ -ray harvest in the first μs is shown for both EARs. Concerning EAR1 a large quantity of γ -rays arriving in the very beginning of the process is observed, corresponding to the very-prompt component. Note that an arbitrary offset of 100 ps has been added for the sake of clarity due to the logarithmic time scale. The energy of the γ -rays arriving in the first ns, see Fig. 4.38 (b), ranges from 0.1 MeV to more than 12 MeV, peaked at a few MeVs and extending to very high energies, reaching tens of GeV. As the time of flight increases, the contribution of the most energetic γ -rays decreases: γ -rays above 12 MeV are not observed in the prompt component and only the X- and γ -rays below 3.5 MeV (delayed component) arrive to the EAR1, being dominant the γ -rays with less than 1 MeV.

Fig. 4.38 (c) shows the time analysis of the γ -rays arriving to the EAR2. Both the same temporal ranges and the same time offset has been considered as EAR1, in order to be consistent with the analysis. It is remarkable the absence of the very-prompt component (below 1 ns), nevertheless, the prompt and delayed contributions (above 1 ns) still remain. In the energy distribution the dominant energies are below 3.5 MeV (see Fig. 4.38 (d)) whereas the γ -rays contribution produced in the first ns is the lesser, around 2 order of magnitude lower compared to the EAR1 results.

These results are consistent with the observation of the output signals of the detectors:

- The area of the γ -flash signal produced in the PPACs, was larger in EAR1 than in EAR2, being consistent with the fact that the contribution of most energetic γ -rays is larger in EAR1 than in EAR2. A similar behaviour was observed in the CVD diamond detector.
- Concerning the out-of-beam detectors, both for the CeBr_3 -PMT and for the plastic detectors, it was observed that the signals registered in the EAR2 showed a lower contribution (small amplitude) in the

beginning followed by a dominant pile-up, whereas the signals registered in EAR1 showed at the firsts nanoseconds a higher amplitude that corresponds to the more energetic γ -rays or charged particles detected.

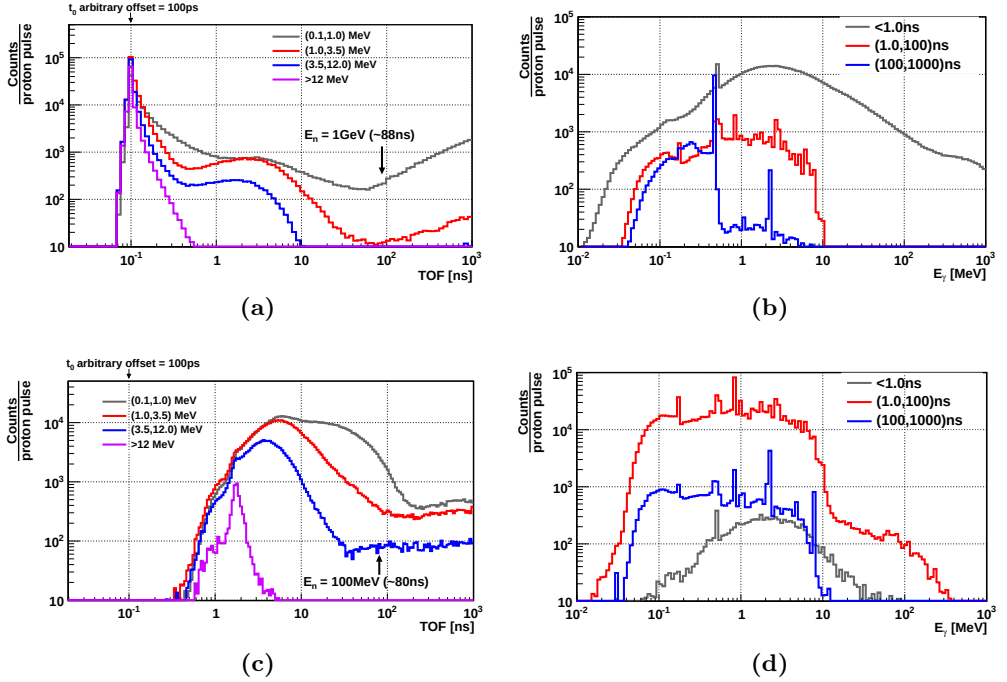


Figure 4.38.: GEANT4 simulations of the γ -rays production. Time and energy distributions calculated for EAR1 and EAR2. In (a), the time distribution is sorted in four energy regions. Note the relevant contribution of the most energetic γ -rays below 1 ns. In (b) is shown that in the first nanosecond the γ -rays cover the full energy range up to 1 GeV, arriving later those produced in secondary reactions. In EAR2, below 1 ns, the primary energy contribution is not observed in (c), and the secondary γ -rays becomes dominant in (d).

4.5. Conclusions to the Chapter 4

This chapter deals with the measurements related to the n_TOF facility at CERN, so that, the scintillator detectors previously characterised in this Thesis work were moved to the n_TOF experiment facility in order to test their behaviour in a real environment, providing new information for their future possible use in new detectors.

The CeBr₃-PMT and CsI(Na)-PMT scintillator detectors were firstly tested by measuring the prompt γ -ray emission by the neutron capture in the $^{197}\text{Au}(n,\gamma)$ and $^{nat}\text{Ag}(n,\gamma)$ reactions. Then, the prompt- γ 's produced in the neutron-induced fission $^{235}\text{U}(n,f)$ reaction were measured in coincidence with the PPAC gaseous chambers, in a range of neutron energies from 1 to 100 eV, using the time-of-flight technique. The results were obtained through the use of signal filtering techniques described in Sections 4.2 and 4.3.

The capture measurements allowed to tune-up the scintillator's setup, and its results confirm the suitability of these radiation detectors and the analysis techniques used in this work, to efficiently detect the prompt γ -rays emitted from (n, γ) reactions.

Concerning the prompt- γ fission detection in coincidence with fission detectors, the detailed analysis here described leads to good results, even though the low statistics gotten because of the very reduced beam time available. These preliminary results confirm that clean spectra can be obtained using small and fast scintillator detectors, paving the way to further experiments to cope with the requests of deeper understanding of the prompt γ -rays produced along the fission process.

Related to the γ -flash, the analysis of the signal produced in several detectors, including those developed in this work, clarified the behaviour of such effect. In EAR1, when comparing to the signals produced by a LaBr₃:Ce crystal, typically used for γ spectroscopy, the reduced volume of the CeBr₃ permit to distinguish more accurately the different components of signals produced by the γ -flash. The deposited energy by the γ -flash even in a so small crystal, would be larger than 10 MeV and a fraction of the pulses are higher, in terms of amplitude, than the dynamic range of the DAQ system, so producing a saturation problem. In order to overcome this

issue, a signal attenuator has been designed and its suitability has been proved using in combination with the CsI(Na)-PMT detector.

Comparing results from different n_TOF campaigns, it can be deduced that the larger the diameter of the second collimator, the larger the amplitude of the γ -flash signals detected by the CeBr₃-PMT detector.

A test was performed setting thick lead-filters in-beam. When no filter was set in beam, the most of the γ -flash pulses detected by the CeBr₃-PMT were saturated (77 %). When the lead filters were used the number of saturated pulses was reduced, as the thickness increased. It can be concluded that the effect of setting thick lead filters in the beam lead to a severe reduction of the γ -flash, reinforcing the idea of the principal role of primary very-high energy γ -rays coming from the spallation target through the beam pipe.

Looking at the temporal structure of the γ -flash pulses, the time distribution of the PPACs first-arriving pulses as well as the second-arriving for an anode, show that the first-arriving ones are detected in the first range of 5 ns, whereas the second-ones arrives spread over a range up to some 100 ns. The CVD diamond detector confirms that the second-arriving pulses are also detected, more scarcely and spread along the following tenths to hundreds of ns.

The γ -flash pulses produced by the plastic scintillator when placed outside the beam, show a wider profile than the registered by a cosmic- μ alone, supporting the idea of the second-arriving prompt signals are due to the conversion of the very-high energy γ -rays in charged particles being later detected out of the beam.

The γ -flash-related measurements performed in the EAR2, in spite of the poor time of flight resolution due to the shorter beam line, shows a severe reduction of the very-prompt component contribution in the in-beam detectors: PPAC and CVD diamond. Concerning the CeBr₃-PMT and the plastic scintillator γ -flash-related signals, two main contributions were observed: those arriving in the firsts 30 ns, and then a larger one after 30 ns. Both detectors showed a similar behaviour despite the low γ -ray efficiency of the plastic.

The analysis of the simulation of the γ -rays produced after the high ener-

getic processes in the spallation target supports the results of the measurements carried out, showing in EAR1 a prominent source of energetic γ -rays in the first ns of time-of-flight, and, conversely, a noteworthy reduction of this γ -rays very-prompt contribution in the EAR2.

5. Summary and conclusions

Summary

This thesis work has been carried out in the GENP group of the USC, in the frame of the study and development of new and better performing detectors. Part of the acquired skills were then focused on the study of radiation detectors based on fast scintillator inorganic-crystals coupled to different photodetectors such as new photomultiplier tubes and PIN diodes. The CERN-n_TOF facility brought a unique opportunity to perform tests looking for the limits in the detection of γ -rays and charged particles in a demanding environment, and measuring very short times having as very precise timing the proton pulse impinging at the n_TOF spallation target. Different fast scintillators were tested, coupled to different photosensors, and different signal processing methods have been discussed.

The problems arising when dealing with signals coming from fast scintillator detectors have been discussed in Chapter 1. Specific solutions, including the development of dedicated electronic circuits, were tested before their further implementation in several experimental set-ups. In particular, simple solutions were found to condition the output signal of different detectors, based on fast crystals as CeBr_3 , CeF_3 and $\text{CsI}(\text{Na})$. The output was firstly analysed at the USC-GENP lab using the traditional spectroscopic chain as well as fast flash-ADC acquisition systems, and then at the CERN-n_TOF experimental areas.

The detectors linearity, energy resolution and time resolution, were firstly measured for γ -rays emitted by different radioactive sources in a range from 121 keV to 4.444 MeV. Even though the reduced photopeak efficiencies of such small size detectors, high detection efficiencies all along a wide range of incident energies were attained. The design of an attenuator for the output signal from the $\text{CsI}(\text{Na})$ scintillator avoid distortion

effects caused in the flash-ADC acquisition systems when the input signal amplitude exceeds its full scale. Moreover, the capability to detect β particles as well as α particles were studied. To do this, new methods based on the Pulse Shape Analysis technique have been developed looking for information on the kind of the incident radiation through detectors. By means of the observables defined for such signals, PSA has been performed to discriminate α particles from γ -rays and its modest success is discussed. The comparisons between the pulse shape analysis of the γ -rays and MIPs -both β particles and cosmic-rays- show that using these crystals does not allow a good identification of the kind of these impinging radiation. The results from the study of prompt γ -rays from both neutron capture and fission reactions have been presented, and the the γ -flash effect has been discussed.

One of the goals of this work was the search for scintillator detectors fast enough to allow detection of γ -rays and charged particles at very short time from the so-called γ -flash. The presence in the n_TOF experimental areas of such a so strong prompt signal produced in the spallation target, represents the biggest limitation in the upper energy limit that can be reached in measurements at n_TOF experiments so far.

Conclusions

The main conclusions of this work may be summarised as follows:

- For these relatively small crystals, high efficiency for γ -rays counting and accurate measurement of the deposited energy for β particles have been found, in accordance with the results that have been obtained by simulations using the EnsarRoot framework.
- The reaction (n,γ) for isotopes ^{107}Ag , ^{109}Ag and ^{197}Au , were measured in a range of neutron energies from 1 to 100 eV by the Time-of-Flight technique. Despite the low statistics available, due to the very reduced acceptance angle defined by the small size of the detectors, the usefulness of this technique was proven to detect prompt γ -rays from capture reactions in a noisy environment.
- The prompt γ -rays emitted from reaction $^{235}\text{U}(n,f)$ were measured

in parallel to the PPACs reaction chamber, in a range of neutron energies from 1 to 100 eV by means of the coincidence method. The overall statistics was low but, nevertheless, the robustness of the coincidence method using the specifically developed software routines was proven, allowing to select the γ -rays from a tagged fission reaction.

- Using the detectors developed in this work, the n_TOF γ -flash has been characterised in both experimental areas, EAR1 and EAR2. It can be deduced that the main contribution is coming from the hard γ -rays originated after the spallation process produced by the impinging protons on the lead target, followed by its conversion in high-energy forward focused e^+e^- pairs. Furthermore, the results were compared with different solid state and gaseous detectors used in the n_TOF experiment, as well as with the simulations performed by other n_TOF groups, confirming such hypothesis.

There is a promising outlook for using small and fast crystal scintillators in order to develop new experiments in coincidence with other detectors, reaching high efficiency at high counting rates and high background, as it is produced by the γ -flash of the spallation targets.

Conclusions

6. Resumen en castellano

La investigación en Física Nuclear experimental necesita experimentos que requieren detectores específicos cuya precisión, en términos de resolución en energía y resolución temporal, sea la mejor posible. Debido a esto, es necesario desarrollar nuevos detectores al mismo tiempo que los continuos avances en los materiales y técnicas usados para la detección de núcleos ligeros, partículas cargadas y radiación γ producidos en procesos nucleares. La mayoría de estos detectores están basados en materiales centelleadores, que pueden ser tanto plásticos (orgánicos) como cristales inorgánicos. El objetivo de este trabajo consiste en la caracterización de diferentes detectores nucleares basados en cristales centelleadores y su posible uso en la detección de radiación γ proveniente de procesos nucleares tales como la fisión nuclear o la captura neutrónica.

A lo largo de la segunda mitad del siglo XX se han realizado numerosos estudios sobre detectores centelleadores. En la última década, la mejora de los procesos de fabricación de los cristales y el desarrollo de fotodetectores ha dado lugar a mejoras en medidas de calorimetría, resolución en energía, identificación de partículas y resolución temporal [1]. En este trabajo se han utilizado los siguientes detectores de radiación: cristales inorgánicos de bromuro de cerio (CeBr_3), yoduro de cesio dopado con sodio ($\text{CsI}(\text{Na})$) y fluoruro de cerio (CeF_3), cuyas principales características se encuentran las Tablas 6.1 y 6.2, acoplados a diferentes fotodetectores, como nuevos tubos fotomultiplicadores y diodos PIN. Además de esto, se ha hecho uso de plásticos centelleadores muy rápidos para tratar de discriminar partículas cargadas de radiación γ .

Estos detectores han sido probados tanto en el laboratorio de desarrollo de detectores situado en la Universidad de Santiago de Compostela así como en la instalación nTOF en el Consejo Europeo para la Investigación Nuclear, CERN, situado en Ginebra (Suiza).

El uso de estos detectores rápidos implica una serie de problemas a la ho-

Cristal centelleador	CsI(Na)	CeBr ₃	CeF ₃
Densidad (g/cm ³)	4.51	5.20	6.16
Constante de bajada, τ (ns)	630	18-20	5,27
Pico de emisión, λ (nm)	420	380	300,340
L.Y. (ph/keV)	35-42	45-60	4.3
Índice de refracción, n	1.84	2.09	1.62
Estructura cristalina	Cúbica	Hexagonal	Hexagonal
Z_{eff}	54	45.9	53
Higroscopicidad	Sí	Sí	No

Cuadro 6.1.: Principales características de los cristales centelleadores usados en este trabajo: CeBr₃, CsI(Na) y CeF₃.

Cristales centelleadores	CeBr ₃	CsI(Na)	CeF ₃ _L50	CeF ₃ _L40
Dimensiones(mm ³)	18x18x25	18x18x25	18x18x50	18x18x40
Acabado	Pulido	Pulido	No pulido	Pulido
Encapsulado por	Scionix	USC	USC	USC
Fabricante	Scionix	MolTech	MolTech	MolTech

Cuadro 6.2.: Dimensiones, acabado, encapsulamiento e información de fabricación de los cristales utilizados en este trabajo.

ra de obtener la información contenida en las señales que se han producido por la interacción de partículas cargadas o radiación gamma. Para resolver estos problemas, se han propuesto una serie de soluciones que consistirían, por un lado, en el desarrollo de circuitos electrónicos y por otro, el uso de filtros digitales para el posterior análisis de la señales adquiridas y digitalizadas por parte de sistemas de adquisición tales como osciloscopios o módulos conversores analógico-digitales usados comúnmente en instalaciones de experimentos dedicados a la Física Nuclear.

Dentro de las soluciones relacionadas con los circuitos electrónicos, se encuentra el desarrollo de una tarjeta electrónica basada en la combinación de filtros activos. Esta tarjeta actúa sobre la señal de los detectores centelleadores como amplificador y modificador de la forma de la señal, adaptándola así a sistemas de espectroscopía, es decir, a módulos amplificadores espectroscópicos que forman parte de la tradicional cadena espectroscópica, ver Fig. 6.1, utilizada comúnmente para averiguar tanto la respuesta lineal del detector como la resolución en energía. Esta tarjeta ha sido específicamente diseñada en dos versiones diferentes: una para el detector CeBr_3 y otra para el $\text{CsI}(\text{Na})$. El uso de esta tarjeta se ha probado utilizando una cadena tradicional espectroscópica resolviendo los problemas de no linealidad y resolución en energía expuestos con anterioridad y se muestran los resultados en las Figs. 6.2.

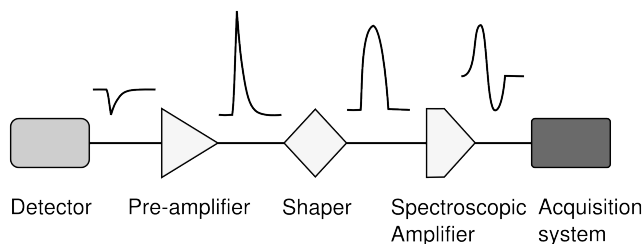
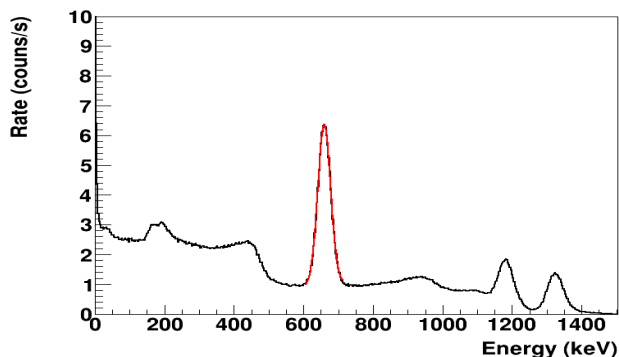
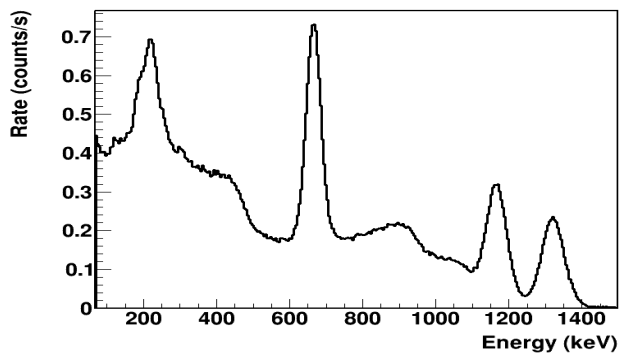


Figura 6.1.: Típica cadena de medida para la medida de la energía depositada, llamada *cadena espectroscópica*. Está compuesta por cinco etapas: el sistema de detección, una etapa preamplificadora, un amplificador que adapta la forma de la señal, el amplificador espectroscópico y por último, el sistema de adquisición. La evolución y modificación de la señal se representa esquemáticamente en la línea.



(a)



(b)

Figura 6.2.: Espectros adquiridos de $^{137}\text{Cs} + ^{60}\text{Co}$ usando las tarjetas electrónicas *Stretcher* para la adaptación de las señales del CeBr_3 , (a), y el $\text{CsI}(\text{Na})$ (b). Los problemas de no-linealidad han sido resueltos.

Los cristales centelleadores tales como el bromuro de lantano y CeBr_3 presentan una emisión de luz muy elevada, denominado por sus siglas en inglés, L.Y., cuando las partículas cargadas o la radiación gamma interactúan con ellos. Esto supone un problema en las primeras etapas de multiplicación de los tubos fotomultiplicadores, que pueden llegar a saturarlos. Para solventar este problema, se ha desarrollado un circuito divisor de voltaje que modifica el zócalo de alimentación proporcionado por el fabricante, Hamamatsu, a través de elementos pasivos, como resistencias,

colocados en paralelo al zócalo original.

Los sistemas de adquisición flash-ADC suelen presentar problemas cuando las señales de entrada superan el rango de amplitud permitido por estos módulos. Un valor característico de este rango suele ser ± 5 V. En algunos casos específicos, la señales proporcionadas por los detectores centelleadores pueden superar estos límites lo que se traduce en efectos no deseados en las señales digitalizadas. Para el detector CsI(Na) se ha desarrollado y probado un atenuador basado en diodos Zener. Al igual que en los dos anteriores casos, el diseño ha sido probado en condiciones reales con resultados óptimos.

Los algoritmos digitales para el análisis de la forma de pulso (PSA) son ampliamente usados para obtener la información contenida en las señales producidas en los detectores de radiación. Los observables de estos filtros son, entre otros, el área del pulso digitalizado, su anchura, amplitud máxima o tiempo de llegada. Además, este tipo de filtros consiguen mejorar problemas como desplazamientos de la línea de base así como el ruido que empeora la calidad de la señal. En este trabajo se han utilizado algoritmos denominados FIR, *Finite Impulse Response*. Estos filtros están bien definidos en el tiempo y no presentan oscilaciones. La señal filtrada de este tipo de filtros consiste en la convolución de la señal de entrada digitalizada con una serie de coeficientes, N , que definen el orden del filtro, como se muestra en la siguiente ecuación:

$$y[n] = \sum_{i=0}^N h_i \cdot g[n - i] \quad (6.1)$$

En este trabajo se han utilizado los filtros FIR triangular y trapezoidal.

Para comprender e intepretar los resultados obtenidos es necesario conocer la interacción entre la radiación γ y las partículas cargadas y la materia así como el proceso de centelleo producido en los materiales que presentan estas características, siendo proporcional a la energía depositada por la radiación. Para comprender el funcionamiento de los cristales centelleadores se ha relizado una simulación Monte Carlo utilizando el programa informático EnsarROOT [37], para averiguar la respuesta de los cristales centelleadores cuando dos fuentes monocromáticas de radiación γ y partí-

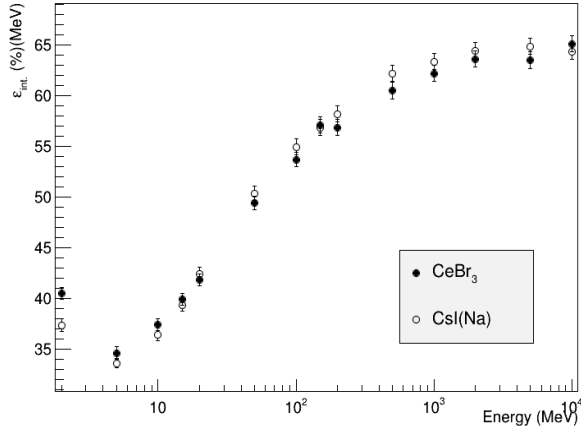


Figura 6.3.: Intrinsic efficiency comparison for bare CeBr₃ and CsI crystals.

culas β o electrones para diferentes energías que comprende un rango de 2 MeV hasta 10 GeV, interaccionan con los cristales de CsI y CeBr₃. Los resultados obtenidos muestran que la eficiencia de detección de radiación γ de estos cristales, a pesar de su pequeño tamaño, es de inicialmente un 40 % a partir de 2 MeV para aumentar hasta un 60 % para energías mayores que 100 MeV. Ver Fig. 6.3. En cuanto a los electrones, se han definido dos observables: el valor medio de la energía depositada en los cristales y el valor más probable, moda. De estos resultados se desprende que tanto la media como la moda aumentan de forma paralela hasta un cierto valor a partir del cual la media continúa aumentando mientras que la moda presenta una zona de plateau. El valor donde se produce esta diferencia de tendencia corresponde con la energía crítica de los cristales a partir del cual la emisión de frenado es dominante sobre la interacción por colisiones con los electrones del medio. Ver Fig. 6.4.

La colección de la luz producida en los cristales centelleadores requiere de un envoltorio adecuado que optimice esta recogida luz. Para ello es necesario utilizar los materiales adecuados. Además, atendiendo a la higroscopicidad de los materiales centelleadores, es necesario encapsularlos para evitar la absorción de la humedad presente en el ambiente por parte de los cristales que empeora la calidad de estos. Los cristales empleados en

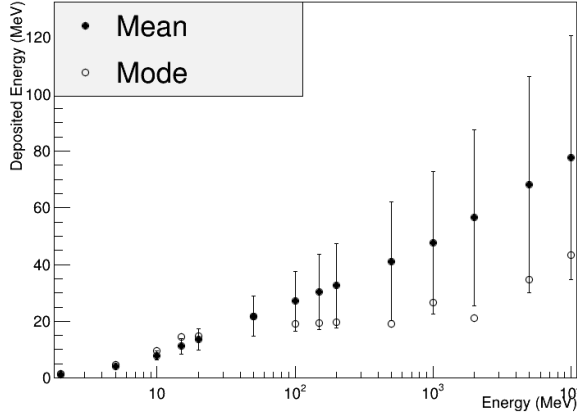


Figura 6.4.: Most probable deposited energy value (mode) and mean deposited energy value (mean) for CeBr_3 for electrons at different initial energies.

este trabajo han sido envueltos y encapsulados en el laboratorio de desarrollo de detectores de la USC, exceptuando el cristal centelleador de CeBr_3 que ha sido encapsulado por el fabricante, Scionix. Para el resto de cristales, se han utilizado dos capas de material ESR de 3M para su envoltorio y un encapsulamiento con una carcasa de aluminio. Uno de los cristales de CeF_3 , cuya longitud es 40 mm, ha sido envuelto con dos tipos del envoltorio: uno completo y uno en el que se ha practicado una pequeña abertura para permitir el paso de partículas α .

Los fotodetectores empleados para la detección de los fotones generados en los cristales centelleadores son cuatro tubos fotomultiplicadores mod. R7600U-200 y un diodo PIN mod. S3204-08, todos fabricados por Hamamatsu. El correcto acoplamiento entre los fotodetectores y los cristales garantiza la máxima transmisión de luz producida a los fotodetectores. Para ello se ha utilizado grasa óptica, BC-630 de Saint-Gobain Crystals, para el acoplamiento entre los cristales CeBr_3 y CeF_3 (con dos longitudes: 40 mm y 50 mm) y tres fotomultiplicadores mod. R7600U-200. Los detectores acoplados reciben los nombres de $\text{CeBr}_3\text{-PMT}$, $\text{CeF}_3\text{-L40-PMT}$ y $\text{CeF}_3\text{-50-PMT}$ respectivamente. El cristal de $\text{CsI}(\text{Na})$, ha sido acoplado a

un fotomultiplicador mod. R7600U-200 utilizando el cemento óptico RTV 681 de Scionix. El detector acoplado recibe el nombre de CsI(Na)-PMT. Por último, este mismo cristal fue acoplado a un diodo PIN cuyo modelo ha sido referenciado con anterioridad utilizando un adhesivo óptico $n = 1.582$ de Meltmount (CsI(Na)-PIN).

A continuación, las técnicas y métodos expuestos con anterioridad se han aplicado para obtener la información de las señales producidas por los detectores. Para ello se han utilizado diferentes tipos de fuentes radiactivas: emisores γ como ^{152}Eu , ^{137}Cs , ^{60}Co and ^{88}Y , un emisor β , ^{90}Sr , una fuente de partículas α , ^{238}Pu , y una fuente de Am-Be, que emite tanto γ como neutrones. Las pruebas realizadas con estas fuentes radiactivas permiten el estudio de los detectores de radiación en un rango de energías desde 121 a 4444 keV.

Para el estudio de la linealidad y la resolución en energía el montaje experimental consta de los detectores CeBr₃-PMT y CsI(Na)-PMT cuya señal de salida es conectada a sus respectivas tarjetas electrónicas *stretcher* cuya salida se conecta a un módulo espectroscópico mod. 2022 de CANBERRA [3]. La salida del amplificador espectroscópico alimenta el analizador multicanal MCA 8000A de AmpTek Inc. [6]. El montaje para el detector CsI(Na)-PIN es similar, salvo que la tarjeta *stretcher* es sustituida por el módulo preamplificador MPR-1 de Mesytec [41]. Para dicho estudio, se ha utilizado la fuente radiactiva ^{152}Eu debido a la emisión de ocho picos de radiación γ de relativa alta intensidad, cuyas energías e intensidades relativas, entre paréntesis, son: 121 (25.6 %), 244 (7.6 %), 344 (26.5 %), 778 (12.9 %), 964 (14.6 %), 1085 (10.2 %), 1111 (13.6 %) y 1408 (21.0 %). La resolución en energía de los detectores se ha calculado, una vez sustraída la contribución del fondo de radiación, a través de una función suma con dos términos: una función gaussina más una función lineal. Los parámetros centro y desviación estándar de la función gaussiana, proporcionan el valor central del fotopico relacionado directamente con la energía y un valor relacionado con la resolución respectivamente. Se han realizado calibraciones energía-centro del fotopico para los detectores CsI(Na)-PMT, CeBr₃-PMT y CsI(Na)-PIN dando como resultado una relación lineal. En cuanto a la resolución en energía obtenida de los fotopicos de los espectros de ^{152}Eu , calculada siguiendo la Ec.

$$R(E) = \frac{FWHM}{E} \times 100 \equiv \frac{2,35\sigma}{E} \times 100 \quad (6.2)$$

donde σ es la desviación estándar de la función gaussiana y FWHM el ancho a la semi-altura del pico, se ha ajustado a una función de la forma

$$R(E) = \frac{p_0}{E^{p_1}} \quad (6.3)$$

para averiguar la dependencia de la resolución en energía en función de la energía. Este ajuste se ha utilizado para calcular la resolución en energía para el fotopico de ^{137}Cs a 662 keV y a una energía igual a 1 MeV, para ser comparado posteriormente con el valor de resolución obtenido a través del ajuste explicado arriba (función gaussiana más función lineal) de la medida de un espectro de ^{137}Cs . Se ha estudiado el comportamiento de los detectores en un rango de temperatura cercano a la temperatura ambiente, utilizando el montaje experimental descrito anteriormente. Además se ha utilizado una sonda de temperatura mod. para monitorizarla. Los datos obtenidos a través de estas medidas confirman que la resolución en energía no se ve afectada en la región de temperatura estudiada, estando de acuerdo con los resultados de las Refs. [23] y [47].

Los detectores de CeF_3 presentan una pobre resolución en energía, dificultando así la capacidad de distinguir fotopicos. Debido a su falta de higroscopicidad, la medida con partículas α ha sido posible debido a la abertura realizada en el envoltorio del detector CeF_3_L40 . En la Fig. 6.5 se muestra el espectro depositado por las partículas *alpha* emitidas por una fuente radiactiva de ^{238}Pu . Como referencia, se utiliza el espectro adquirido por el mismo detector para radiación γ de 662 keV emitida por el ^{137}Cs . Se observa que la energía depositada en el cristal es menor que la depositda por la radiación γ , debido principalmente a la alta densidad de ionización [44, 45].

La resolución temporal de los detectores $\text{CeBr}_3\text{-PMT}$ y CsI(Na)-PMT se ha medido utilizando el método de coincidencias. Para ello, se ha medido la forma de los pulsos producidos en un plástetico centellador acoplado a un fotomultiplicador y en uno de los detectores colocados en paralelo por el paso de rayos cómicos. La adquisición de las formas de la señal se

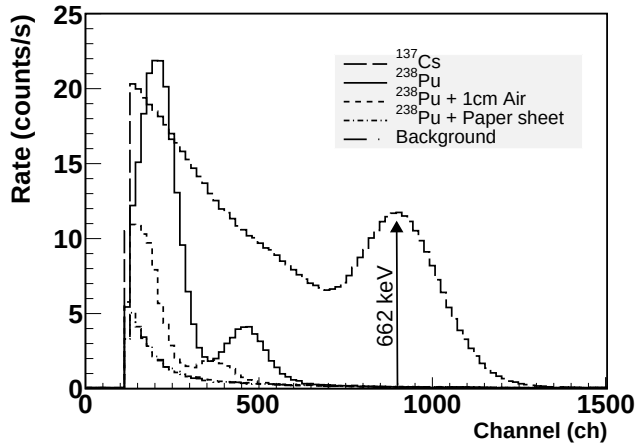


Figura 6.5.: Espectro ^{238}Pu usando CeF_3 para diferentes configuraciones de la medida. El espectro de ^{137}Cs se usa como referencia para la energía depositada.

ha realizado utilizando un osciloscopio fabricado por YOKOGAWA mod. 9140 cuya frecuencia de muestreo es 5 GS/s. Los pulsos producidos en el $\text{CsI}(\text{Na})$ -PMT han sido filtrados usando un filtro triangular para obtener mayor precisión a la hora de calcular el tiempo inicial de los pulsos. Los resultados obtenidos son una resolución temporal de 207 ps para el caso del CeBr_3 -PMT y de 915 ps para el caso del $\text{CsI}(\text{Na})$ -PMT.

El *decay time* de los detectores, CeF_3 _L40-PMT, CeBr_3 -PMT y $\text{CsI}(\text{Na})$ -PMT, se ha obtenido calculando el pulso promedio de un conjunto de formas de pulso proveniente de radiación γ de 662 keV. El *decay time* obtenido es de 4 y 36 ns para el CeF_3 _L40-PMT, 24 ns para el caso del CeBr_3 -PMT y dos componentes de 470 y 2588 ns se han observado para el caso del $\text{CsI}(\text{Na})$ -PMT. Además, se ha realizado una comparación entre los pulsos promedio provenientes de rayos cósmicos (principalmente μs), partículas β y radiación γ . Los pulsos promedio para cada partícula no difieren unos de otros para ambos detectores, CeBr_3 -PMT y $\text{CsI}(\text{Na})$ -PMT, lo que implica que no pueden realizar esta identificación.

Debido a la posibilidad de detección de partículas α por el detector CeF_3 _L40, se ha procedido a tratar de identificar las partículas α de la

radiación γ a través de la definición observables de la señales producidas por el detector. El pulso promedio para cada tipo de partículas confirma que existen diferencias en su forma. Atendiendo a estas diferencias, se definen como observables el área y la pendiente de la recta ajustada al flanco de subida de la señal. Representando ambos observables para cada tipo de partícula, se observa una ligera diferencia, pero no es suficiente para confirmar la identificación.

La instalación n_TOF (Neutron Time Of Flight) es una instalación situada en el CERN dedicada al estudio de reacciones inducidas por neutrones, principalmente la captura radiactiva (n, γ) y la fisión (n, f) siendo de gran interés en los campos de la astrofísica y del desarrollo de nuevas tecnologías dedicadas a la producción de energía nuclear y a la transmutación de residuos radioactivos. Los neutrones son producidos una vez que los grupos protones de 7 ns (rms) y 20 GeV/c procedentes del acelerador (PS) inciden sobre un blanco de espalación. El blanco constituido por plomo está rodeado de un circuito de agua que actúa como moderador. A 185 m se encuentra la sala experimental 1 (EAR1) precedida por la línea de haz 1 en la que se encuentran diferentes elementos que optimizan el haz de neutrones antes de llegar a la sala experimental. Verticalmente y desde el blanco de espalación, se encuentra la sala experimental 2 (EAR2), precedida por la línea de haz 2, que al igual que en la línea de haz 1, dispone de varios elementos para optimizar el haz de neutrones.

Durante la campaña de medidas realizada en 2012 en el experimento n_TOF se realizaron medidas de la radiación prompt- γ emitida en las reacciones de captura neutrónica de los isótopos ^{107}Ag , ^{109}Ag y ^{197}Au para los detectores CeBr₃-PMT y CsI(Na)-PMT. Para ello se desarrolló un algoritmo digital basado en el filtro trapezoizal para calcular el tiempo de inicio de las señales que es clave para la utilización de la técnica de tiempo de vuelo. Se han comparado los resultados obtenidos, siendo estos proporcionales a los datos proporcionados para las secciones eficaces de los tres isótopos proporcionados por la librería CENDL-3.1 para el caso de la Ag y la ENDF/B-VII.1 para el caso del Au.

En la misma campaña se realizaron medidas en coincidencia con los detectores gaseosos, PPAC (Parallel Plate Avalanche Counter), desarrollados y construidos en el IPN d'Orsay (Francia). Este detector, consiste en una

vasija de aluminio que contiene 10 PPACs entre las que se encuentran intercalados 9 blancos como se muestra esquemáticamente en la Fig. 6.6. La radiación prompt- γ emitida por la reacción (n,f) en el penúltimo blanco, ^{235}U , ha sido medida por los detectores $\text{CeBr}_3\text{-PMT}$ y CsI(Na)-PMT . El algoritmo utilizado para las reacciones de captura neutrónica es válido para analizar las señales producidas por los detectores. Un método específico de coincidencia se ha desarrollado para seleccionar los prompt- γ emitidos por la reacción de fisión (n,f). A pesar de la baja estadística, queda probada la validez del método para seleccionar dicha radiación.

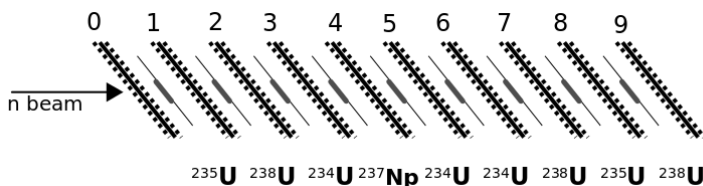


Figura 6.6.: Esquema de la configuración de las PPACs donde los blancos se encuentran intercalados.

Durante el proceso de espalación además de neutrones, se produce una gran cantidad de radiación así como partículas neutras y cargadas. Estos productos de la espalación viajan a través de las líneas de haz 1 y 2 interaccionando con los elementos dispuestos en ellas produciendo nuevas partículas y radiación perturbando el haz de neutrones. La contribución de estas partículas y radiación provoca inconvenientes en las salas experimentales ya que ciega los detectores durante un lapso de tiempo dependiente de la naturaleza y electrónica asociada a los detectores, entorpeciendo la medida de los neutrones más energéticos producidos en el proceso de espalación (ver Fig. 6.7). Este indeseable efecto, se denomina γ -flash.

Los detectores $\text{CeBr}_3\text{-PMT}$, CsI(Na)-PMT han sido utilizados para caracterizar el γ -flash. Las medidas se han realizado durante las campañas de 2012 en la sala experimental 1 y durante la puesta en marcha de 2014 en la sala experimental 2. Se parte de la hipótesis de que el γ -flash es un efecto producido principalmente por la radiación γ producida durante el proceso de espalación y la desintegración de alguno de sus productos. Se ha estudiado el promedio de las señales producidas para el γ -flash para $\text{CeBr}_3\text{-PMT}$, y un plástico centelleador, cuya eficiencia para radiación γ

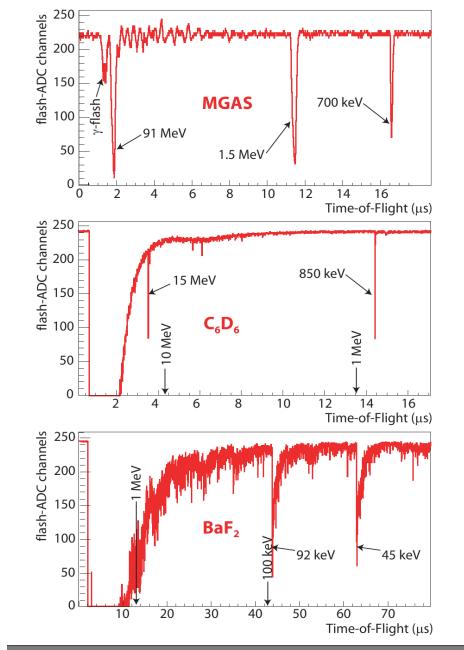


Figura 6.7.: Señales producidas por el γ -flash para diferentes detectores: Micromegas, C6D6 y BaF2.

es muy baja, colocado en coincidencia con el CeBr₃-PMT. Los resultados obtenidos indican que hay una componente denominada very-prompt formada principalmente por radiación γ . Esto también ha sido constatado por detectores de estado sólido, diamante, gaseosos, PPACs. Los resultados obtenidos concuerdan con los obtenidos de las simulaciones realizadas con el software GEANT4 realizadas por otros grupos de la colaboración n_TOF.

Conclusiones Las principales conclusiones de este trabajo son:

- Para estos cristales de tamaño relativamente pequeño, se ha obtenido una alta eficiencia de detección para radiación γ y una medida precisa de la energía depositada por partículas β a través del programa de simulación EnsarRoot.

- La reacción inducida por neutrones (n, γ) para los isótopos ^{107}Ag , ^{109}Ag y ^{197}Au ha sido medida en un rango de energía de los neutrones comprendido entre 1 y 100 eV a través de la técnica de tiempo de vuelo. A pesar de la baja estadística disponible, debido a la muy reducida aceptación angular definida por el tamaño pequeño de los detectores, se ha probado la utilidad del uso de esta técnica para detectar la radiación *prompt- γ* emitida por las reacciones de captura en un ambiente con presencia de ruido.
- La radiación *prompt- γ* emitida por la reacción $^{235}\text{U}(n, f)$ ha sido medida en paralelo a la cámara gaseosa PPAC, en un rango de energías del neutron comprendido entre 1 y 100 eV a través del método de coincidencias. La estadística conseguida ha sido baja, pero, sin embargo, la robustez del método de coincidencias usando las rutinas de software específicas ha sido probado, permitiendo seleccionar la radiación *prompt-gamma* que proviene de una reacción de fisión concreta.
- Usando los detectores utilizados en este trabajo, el *gamma-flash* n_TOF ha sido caracterizado en ambas salas experimentales, EAR1 y EAR2. Puede deducirse que la contribución principal proviene de la emisión de radiación γ que procede del proceso de espalación producido por los protones que inciden en el blanco de plomo, seguido de su conversión en pares e^+e^- focalizados hacia adelante. Los resultados fueron comparados con diferentes detectores de estado sólido y gaseosos utilizados en el experimento n_TOF, así como con las simulaciones realizadas por otros grupos pertenecientes a la colaboración n_TOF, confirmando esta hipótesis.

A. Main characteristics of a signal

- **Baseline** is the reference in terms of voltage or current to which the signal pulse is digitised. Commonly the value for this reference is zero, however, it can be a different constant value and very often the tail of the signals affects the apparent baseline for the next signal, requiring specific hardware or software handling.
- **Pulse height or Amplitude.** It is referred to the distance in voltage or current from the baseline to the most highest absolute value (positive or negative) that the signal pulse achieves.
- **Rising Edge** is the transition from the low to the high amplitude values.
- **Falling Edge** is the transition from the high to the low amplitude values.
- **Rise time** is the time interval in which the signal amplitude evolves from the minimum to the maximum values. The most common definition is the time interval that takes the signal increases from the 10% to the 90% of its amplitude.
- **Fall time** similarly to the rise time, the fall time is most commonly defined as the elapsed time, between the 90% and the 10% of the amplitude when is decreasing.
- **Signal width** is defined as the elapsed time above 50% of its amplitude. It is commonly called: Full Width Half Maximum (FWHM onwards).

B. Voltage Divider

The use of decoupling capacitors is a common technique to supply current between dynodes stages. The E5996 socket, manufactured by Hamamatsu [9], includes this technique with capacitors that are connected following the serial method. Oscilloscope measurements of the PMT signals proceed from a $18 \times 18 \times 25 \text{ mm}^3$ CeBr₃ crystal when irradiated by a ¹³⁷Cs radioactive source, show that the amplitude of the pulses is about 5 V and their FWHM of 10 ns, falling exponentially from the maximum. The mean current above half-maximum is approximately 75 mA, the peak current exceed 100 mA, and the integrated charge, Q, is 10 nC. In order to maintain the detector within the linear region, see Fig. 1.4, the capacitance value C between the 10th dynode and the anode, should be around 100 times the output charge as follows:

$$C > 100 \cdot \frac{Q}{V_{10^{th}dy}}, \quad (\text{B.1})$$

where V is the voltage supply between the last dynode and the anode,

$$V_{10^{th}dy} = |-800 \text{ V}| \frac{220 \text{ k}\Omega}{2700 \text{ k}\Omega} = 64 \text{ V} \quad (\text{B.2})$$

Thus,

$$C > 16 \text{ nF} \quad (\text{B.3})$$

The original capacitor has 10 nF. Therefore, the C value shall be increased. A capacitance value of 22 nF was welded in parallel to C (C₃ in the scheme show in Fig. B.1), left) of the socket E678-32B from Hamamatsu [8]. So that, a variation of voltage between last dynode and anode is less than 1%.

$$\Delta V = \frac{\Delta Q}{C} = \frac{14 \text{ nC}}{32 \text{ nF}} = 0.44 \text{ V} \quad (\text{B.4})$$

B. Voltage Divider

Electrodes	K	Dy1	Dy2	Dy3	Dy4	Dy5	Dy6	Dy7	Dy8	Dy9	Dy10	P
Hamamatsu	1.5	1.5	1.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
δV @ -800 V	96	96	96	64	64	64	64	64	64	64	64	64
This work	2.2	2.2	2.2	1.0	1.0	1.0	1.0	1.0	1.47	1.47	1.47	
δV @ -698 V	96	96	96	43.6	43.6	43.6	43.6	43.6	64	64	64	
δV @ -710 V	97.6	97.6	97.6	44.4	44.4	44.4	44.4	44.4	65.1	65.1	65.1	

Table B.1.: Voltage dividers distribution from Hamamatsu E5996 socket and the modified design in This work. Below every VD design (Hamamatsu and This work) the potential difference between electrodes at -800 V, -698 V and -710 V is shown.

With the original E5996 socket values, the recommended bias voltage is -800 V, the whole chain resistance is $R_{chain} = 2.75 \text{ M}\Omega$, and the current in the chain is $291 \text{ }\mu\text{A}$. With the modified VD the three first inter-stage voltages and the three last ones remains unchanged when the bias voltage is -698 V, being so the current $291 \text{ }\mu\text{A}$, as it was in the original design. Nevertheless, a gain reduction is achieved in the five intermediate stages by the reduction of these resistors (R_4 to R_8) soldering in parallel five $220 \text{ k}\Omega$ resistors with the original ones of $470 \text{ k}\Omega$, to give values of $150 \text{ k}\Omega$. (see Fig. B.1). The total VD resistance value after modifications is $2.4 \text{ M}\Omega$ instead of the original value of $2.75 \text{ M}\Omega$ and the gain is reduced due to the decrease of the voltage between dynodes Dy_3 and Dy_8 so that voltage applied between latter stages is enhanced. This is a corrective action to avoid output saturation caused by an increment in the electron density in the latter stages that leads to space charge effects disturbing the electron current. The ratio between dynode Dy_8 and the anode has been increased as it is shows in Table B.1. Using this modified socket the best energy resolution result at 662 keV it was obtained by a bias voltage of -710 V. The voltage distribution for $V_{bias} = -710 \text{ V}$ can be also seen in Table B.1.

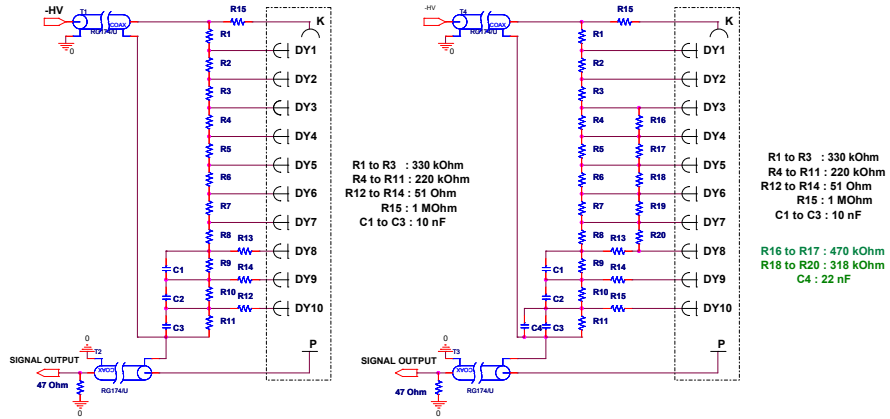


Figure B.1.: Hamamatsu E5996 Voltage Divider (left). Modified version of the original Hamamatsu design to make it suitable for the very fast signals produced by high L.Y. crystals (right).

C. Equivalent Series Resistance (ESR) in capacitors

An ideal capacitor of nominal electrostatic capacitance C has an impedance given by

$$Z = \frac{1}{j\omega C} \quad (\text{C.1})$$

The impedance $|Z|$ decreases inversely with the angular frequency ω . However, in actual capacitors a more complex behaviour is found, that can be simulated by introducing, resistive (ESR) and inductive (ESL) effects as contributing to the actual impedance; this is sketched in Fig. C.1, where an insulator resistor (IR) is added in parallel with C , due to the resistive contribution of the dielectric material (actual insulation resistance for UHF capacitors can be as high as $10^5 \text{ M}\Omega$).

In Fig. C.2 is a generic representation of the realistic impedance behaviour of an actual capacitor. The dotted red line shows the ideal behaviour of Eq. C.1, that is roughly followed up to a *critical* frequency, called self-resonant frequency, where the parasitic inductance starts to dominate. This inductance is due to electrodes, leads and the PCB where the capacitor were physically soldered (needless to say, the miniaturisation

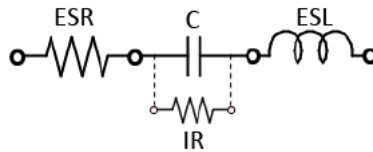


Figure C.1.: Equivalent circuit representation of an actual capacitor. Courtesy of Murata Electronics [82].

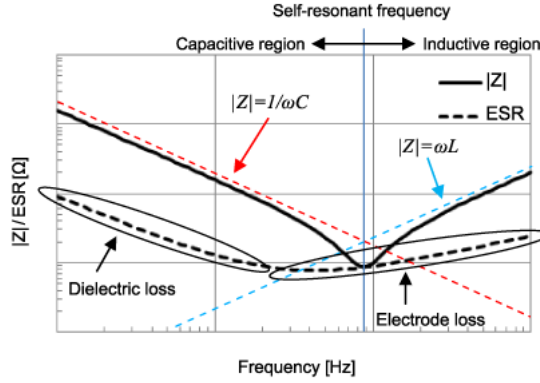


Figure C.2.: Frequency response of an actual capacitor. The self-resonant frequency typically ranges from a few MHz to a few GHz. Courtesy of Murata Electronics [82].

of nowadays circuitry helps to reduce this parasitic effects). This fact leads to the frequency characteristics of the impedance to be V-shaped, shown in Fig. C.2. In the ideal case, the ESR contribution is zero; the ESR due to the dielectric losses behaves dropping linearly with frequency but above a certain value becomes counterweighted with the electrode loss acting with a positive slope in frequency. Typical values of ESR for higher-quality UHF capacitors are below 50 mΩ up to 600 MΩ, raising to double this value at 2 GHz. All in all, the final curve becomes U-shaped, around the self-resonant frequency, typically ranges from a few MHz to a few GHz [82]. A quality factor (Q) is often specified by manufacturers; it is defined as the ratio of the energy stored to that dissipated at a fixed frequency. For the higher quality capacitors Q should be as high as 2000 at 1 MHz, but this value can be hundred times lower for components not specified for UHF, worsening again one order of magnitude above 1 GHz.

This particular behaviour is of relevance when designing circuits for very-high frequency signals since this enable the designer to determine, for instance, the effect of capacitors in the PMT VDs or the noise suppression capabilities on a power supply line [82].

D. *Stretcher PCBs desing*

The input signal is a current type, in order to convert it into a voltage type and to condition the impedance of the LEMO connector and the cable RG 174/U an impedance of $50\ \Omega$ is included at the input of the design.

The design, shows in Fig. D.1 consists of three active stages that are described below:

The signal from the CeBr₃-PMT is firstly conditioned prior to attack the Operation Amplifier, OA, to get proper operation within the bandwidth of the OA, is the LM6172 High Speed manufactured by Texas Instrument Incorporation [83], whose unity-gain bandwidth is 100 MHz . Since the CeBr₃-PMT rise time is around 10 ns, a RC passive filter is then arranged the bypass capacitor C₁. The capacitor C arranged in passive filter must be properly chosen in order to minimise the contribution of noise effects due to the equivalent series of resistance, ESR, that appear at high frequencies region. See Appendix C for a more detailed explanation.

The second stage is an active low-pass filter including a resistor, R19 in series to a in parallel RC chain formed by R2 and C2, to control the gain of the filter and not to disturb the frequency, $1/R2C2 = 0.5\ \text{MHz}$, of the filter. At this point, the signal is still not conditioned for the SA input requirements. Two more active filter stages are needed: two low-pass filters, whose cut-off frequency is $1/R18C6 = 1\ \text{MHz}$ and $1/R13C11 = 45\ \text{kHz}$ respectively for the second and the third stages. In both stages the OA LM6172 Dual High Speed whose unity-gain bandwidth is 100 MHz from Texas Instrument has been used/chosen. The output signal of the circuit meets the input requirements for the SA CANBERRA 2022. See Fig. D.2 (e)

An analog method has been followed to desing the *stretcher* circuit for the CsI(Na)-PMT.

The circuit has been designed and simulated using PSpice software, the

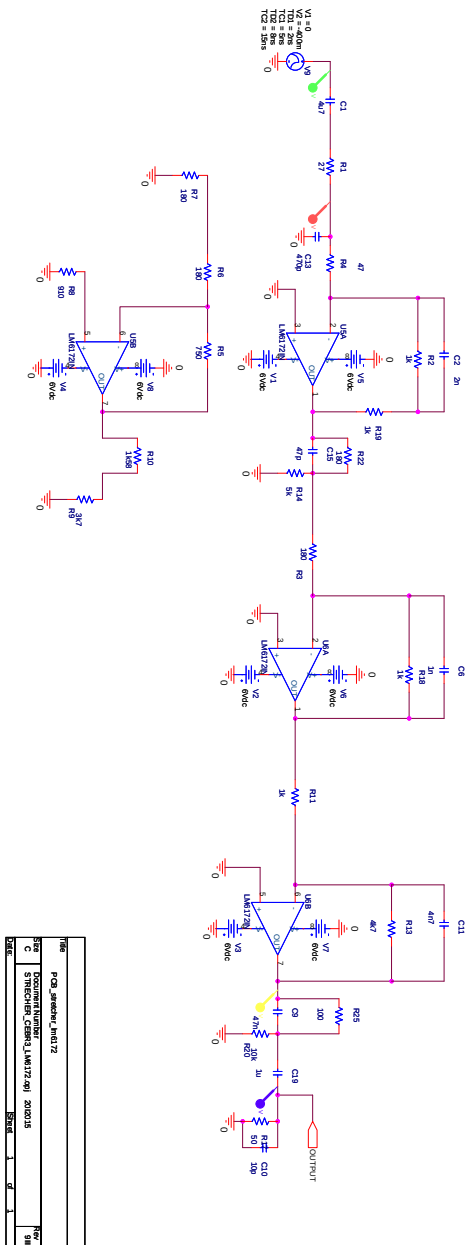


Figure D.1.: Stretcher circuit design for CeBr₃-PMT

PCB based on such design is implemented. Once the components were welded, the operation of the circuit is tested using a test probe connected to the oscilloscope YOKOGAWA DL9140 5GS/s 1GHz when the detector is providing signals from the detection of γ -rays from a radioactive source. The final value of the components have been determined by trial and error because of the presence of spurious impedances, among others, induces by the tracks.

Transfer function

When analysing the behaviour of an electronic circuit, applying mathematical properties simplify the calculations to find out the behaviour in the linear range of such circuit. Here most important properties are presented:

Superposition principle: For any two arbitrary input signals, V_{in1} and V_{in2} , the sum of both signals $V_{in1}+V_{in2}$, corresponds the sum of the independent output signals $V_{out1}+V_{out2}$.

Concepts such as *Impulse response* and *Transfer function* must be also introduced to understand the mathematical properties that will be exposed as follows:

Impulse response. The impulse response $h(t)$ is the response of a system to a delta function like input pulse.

$$V_{in} = \delta(t) \quad V_{out} = h(t) \quad (D.1)$$

Transfer function. The transfer function $H(w)$ is the Fourier transform of the impulse response.

$$H(\omega) = \frac{1}{\sqrt{2\pi}} \int \exp^{-i\omega t} h(t) dt \quad (D.2)$$

A low passive filter, $R1 \cdot C13 = 13$ ns, is arranged previously to the first active stage in order to condition the input signal to the characteristics of the operation amplifier, onwards OA, LM6172 manufactured by TEXAS INSTRUMENTS [83]. This can be observed in the transfer function of such active filter:

$$H(\omega) = \frac{R2 + R3}{R1} \cdot \frac{1 + \omega \frac{R2R3}{R2+R3}C2}{1 + j\omega R2C2} \quad (D.3)$$

The output signal of this stage therefore, is inverted, amplified and integrated, what implies a wider signal. See Fig. D.2 (a).

The output signal shows an undershoot which can be a problem when measuring pulse heights what is related to spectroscopy, especially at high rates producing a baseline shift which means a broaden of the photopeaks and, therefore, worsening of energy resolution. Such undershoot is caused by factor $1+j\omega R2C2$ in Eq D.3, so to remove this undesirable effect, a so-called pole-zero cancellation circuit is arranged after the first active filter. Such circuit consists of a net of passive components, resistors and capacitors whose transfer function is

$$H(\omega) = \frac{1}{\sqrt{2\pi}} A \frac{1 + j\omega R22R14}{1 + j\omega AR22R14} \quad \text{where} \quad A = \frac{R14}{R22 + R14} \quad (D.4)$$

In this case, $A = 0.96$ and $R22R14 = 8.5$ ns which is a value close to 13 ns. The PSpice time domain simulation confirms the effectiveness of this PZ cancellation method. See fig. D.2 (b). At this point, the signal is not still conditioned for the SA input requirements. Two more active filter stages are required: two low-pass filter whose configuration is inverting. The transfer function of both filters are, for the second active filter:

$$H(\omega) = -\frac{R18}{R3} \frac{1}{1 + j\omega R18C6} \quad (D.5)$$

where $A = \frac{R18}{R3} = 5$ and $R18C6 = 1\mu s$

for the third active filter:

$$H(\omega) = -\frac{R13}{R11} \frac{1}{1 + j\omega R13C11} \quad (D.6)$$

where $A = \frac{R13}{R11} = 5$ and $R13C11 = 22\mu s$

The output signal at this stage is shown in Fig. D.2 (c)

The undershoot at this stage is corrected by the PZ cancellation circuit, where

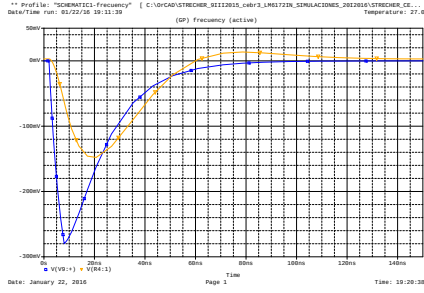
$$R20C9 = 4.7\mu s \quad (D.7)$$

The output signal at this stage is shown in Fig. D.2 (d).

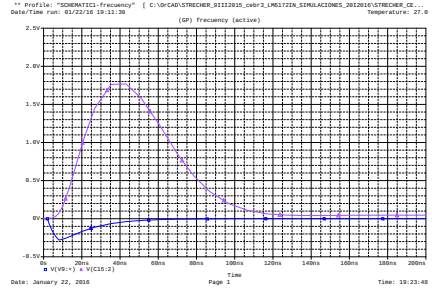
A capacitor, C19 is arranged in series after the PZ cancellation stage in order to eliminate any DC contribution.

The CsI(Na)-PMT *Stretcher PCB* design is shown in Fig. D.3. The Operation Amplifier, OA, used in this desing is the High Speed AD8056 manufactured by Analog Devices Inc., whose unity-gain bandwidth is 300 MHz [84].

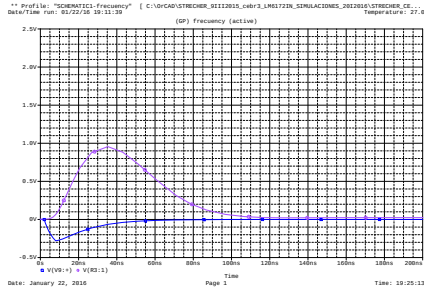
D. Stretcher PCBs desing



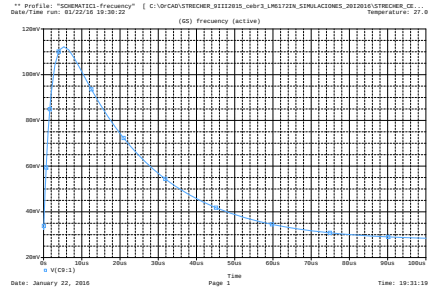
(a) Input signal (blue). Shaped signal after C1 (yellow)



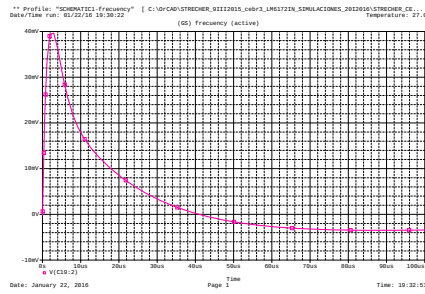
(b) First active filter output



(c) PZ cancellation output



(d) Third active filter output



(e) Circuit output

Figure D.2.: Signals at different stages of the conditioning circuit simulated using PSpice for CeBr₃-PMT.

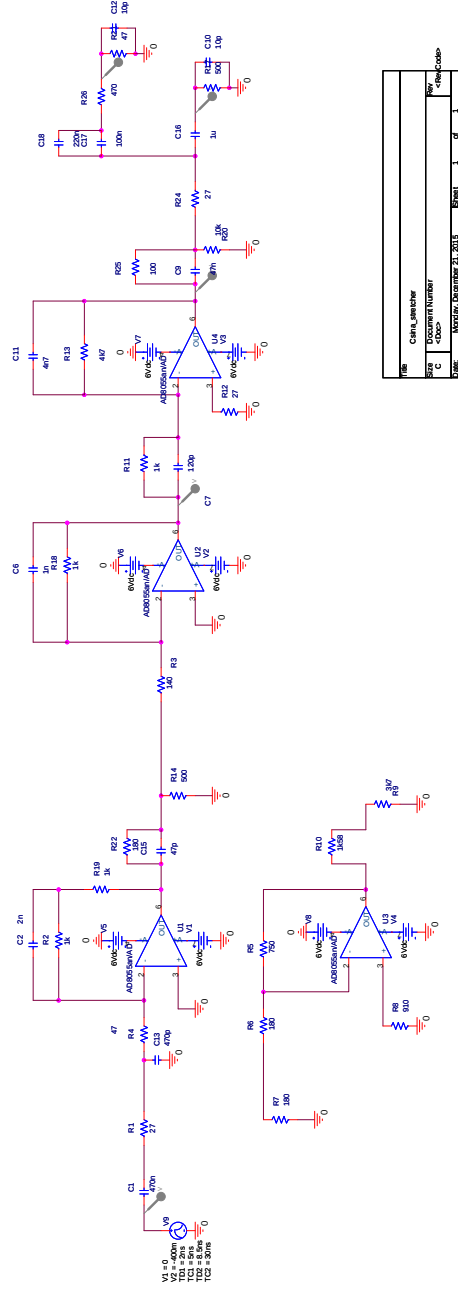


Figure D.3.: Stretcher circuit design for CsI(Na)-PMT.

E. Bethe-Bloch formula

$$-\frac{dE}{dx} = \frac{4\pi n z^2 Z^2 e^4}{m_e v^2} \left\{ \ln \frac{2m_e c^2}{I \left[1 - \left(\frac{v}{c} \right)^2 \right]} - \left(\frac{v}{c} \right)^2 \right\} \quad (\text{E.1})$$

where n is the electron density of the material and Z its atomic number, m_e the electron mass, v is the speed and ze the charge of the particle, c the speed of light in vacuum and I is a tabulated parameter having the meaning of some kind of mean excitation potential of the stopping material [85].

The maximum energy transferred in a collision to a free electron atom by an incident particle with mass M , is given by:

$$T_{max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2} \quad (\text{E.2})$$

with $\beta = \frac{v}{c}$ and $\gamma = \frac{1}{\sqrt{1-\beta^2}}$.

Commonly, the Eq. E.1 is rearranged taking into account the maximum energy transferred (Eq. E.2) and when some corrections are added:

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] \quad (\text{E.3})$$

In Eq. E.3, $K = 4\pi N_A r_e^2 m_e c^2$ where N_A is the Avogadro's number and the classical electron radius $r_e = e/4\pi\epsilon_0 m_e c^2$. The term $\delta/2$ accounts for the density effect correction to ionization energy loss. As the particle energy increases, the distance-collision contribution increases as $\ln(\beta\gamma)$, neglecting polarisation effects in the material thus, the term $\delta/2$ is introduced in Bethe-Bloch formula E.3:

$$\delta/2 \longrightarrow \ln\left(\frac{\hbar\omega_p}{I}\right) + \ln(\beta\gamma) - \frac{1}{2} \quad (\text{E.4})$$

where $\hbar\omega_p = \sqrt{4\pi N_e r_e^3 m_e c^2 / \alpha}$ is the plasma energy of the medium and α the fine structure constant.

F. EnsarRoot

EnsarRoot [37][86] is the simulation and analysis framework for the ENSAR Project [87], under the Research Joint Action, SiNuRSE [88] and it is intended to solve problems identified in the simulation of complex nuclear physics experiments. EnsarRoot inherits most of its features from the FairRoot library [89] which is fully based on the ROOT system [90]. The framework uses the Virtual Monte Carlo concept which allows to perform simulations using different Monte Carlo engines such as Geant3, Geant4 or Fluka [91, 92, 93] without changing the user code. The framework also delivers base classes which enable the users to construct their detector and analysis tasks in a simple way. The event reconstruction is also a feature of such framework, that also provides a generic track follower based on Geant4 which allows precise and fast tracking algorithm developments [94].

EnsarRoot, based on the FairRoot library, includes event generators and specific physics lists for nuclear physics experiments, as well as examples of simple set-ups. The user is able to create simulated data and perform analysis within the same framework. It also provides an interface for track visualisation event-by-event and the detector geometry, see Fig. F.1.

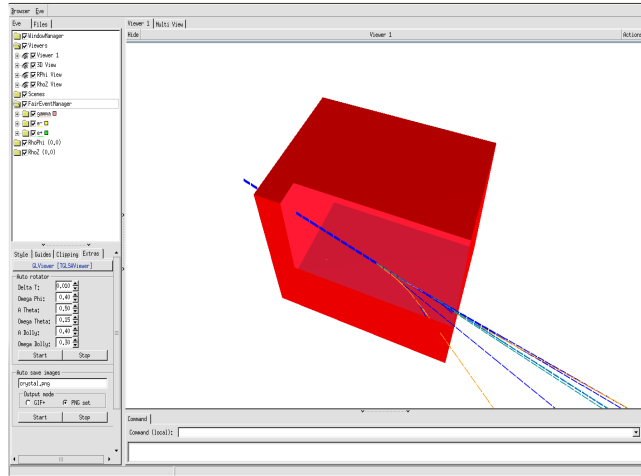


Figure F.1.: Event visualiser for the EnsarRoot framework [37]. A scintillator crystal is 3D sketched and the traces for different particles when an incident γ -ray hits the crystal are distinguished.

G. Spectra from EnsarRoot simulations

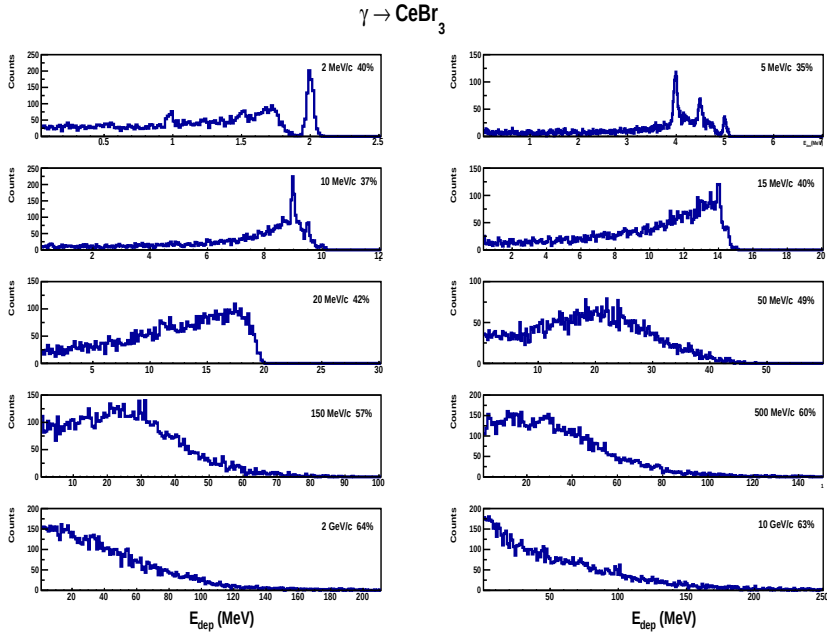


Figure G.1.: CeBr₃ bare crystal. Energy deposited spectra at different initial momentum. Incident particles: γ -rays.

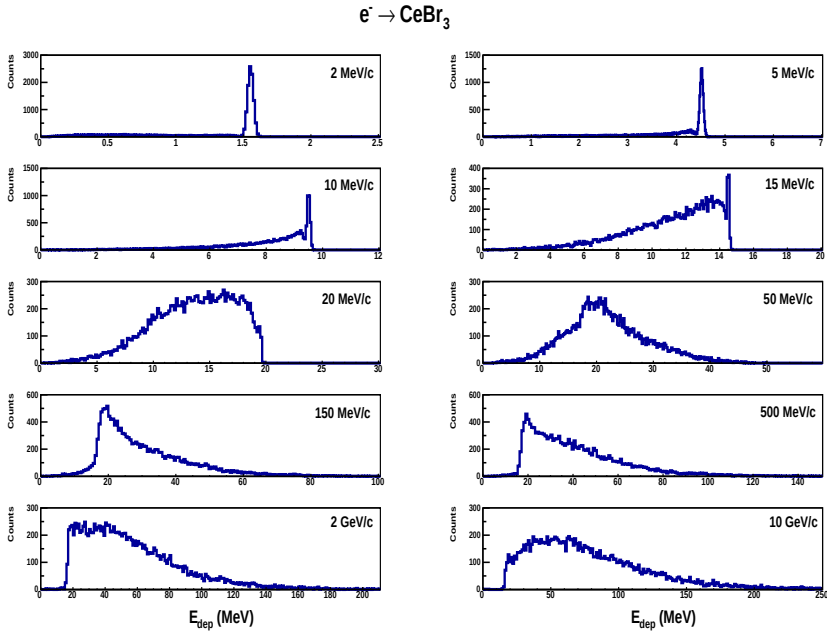


Figure G.2.: CeBr_3 bare crystal. Energy deposited spectra at different initial momentum. Incident particles: e^- .

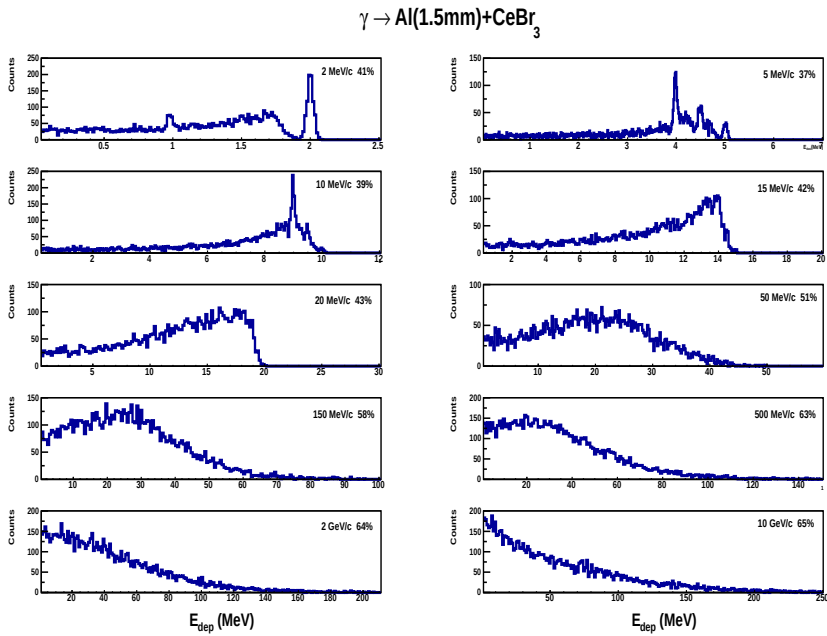


Figure G.3.: CeBr_3 bare crystal+Al foil 1.5 mm. Energy deposited spectra at different initial momentum. Incident particles: γ -rays.

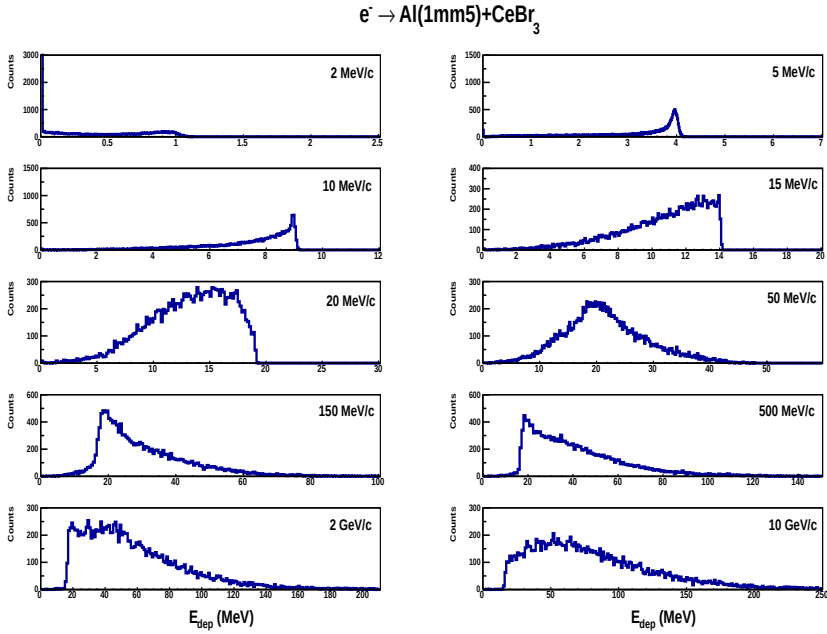


Figure G.4.: CeBr_3 bare crystal+Al foil 1.5 mm. Energy deposited spectra at different initial momentum. Incident particles: e^- .

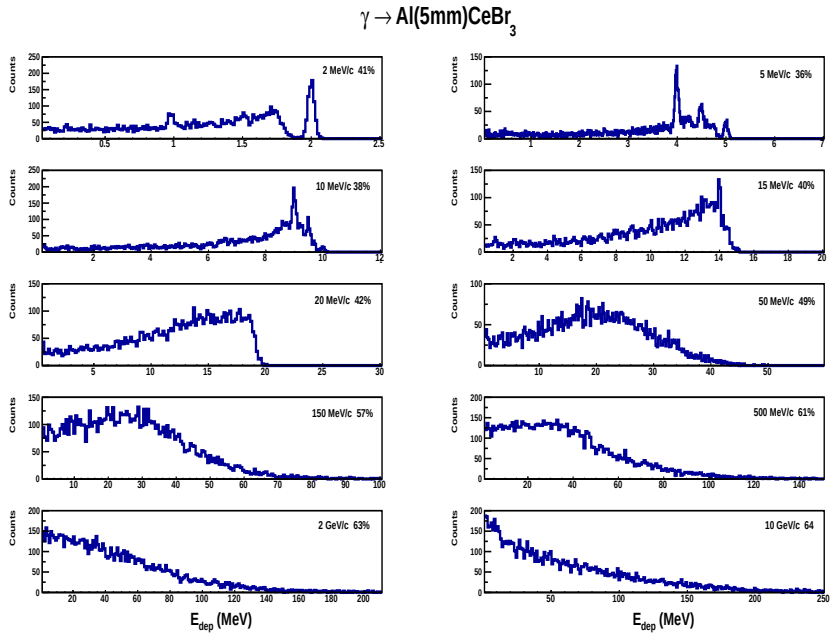


Figure G.5.: CeBr_3 bare crystal+Al foil 5 mm. Energy deposited spectra at different initial momentum. Incident particles: γ -rays.

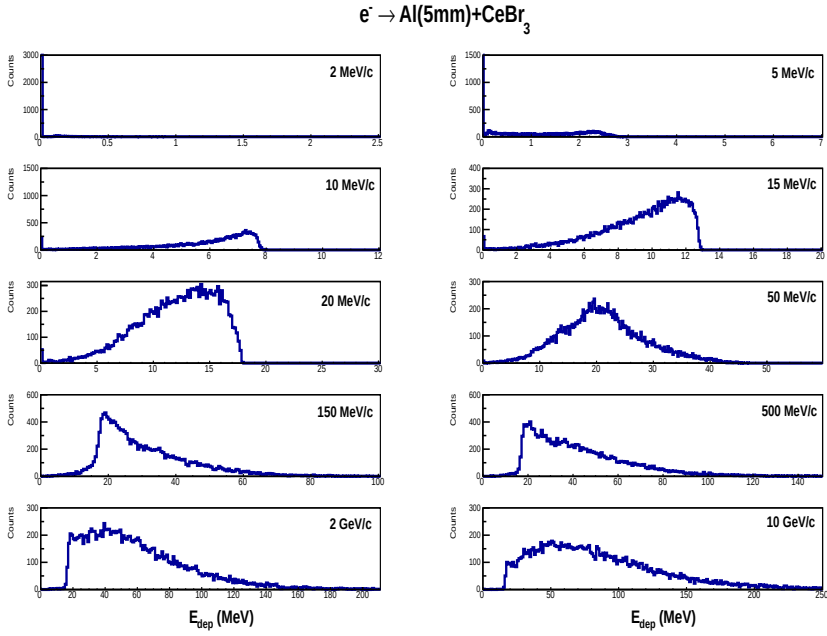


Figure G.6.: CeBr_3 bare crystal+Al foil 5 mm. Energy deposited spectra at different initial momentum. Incident particles: e^- .

CsI(Na) simulations

$\gamma \rightarrow \text{CsI:Na}$

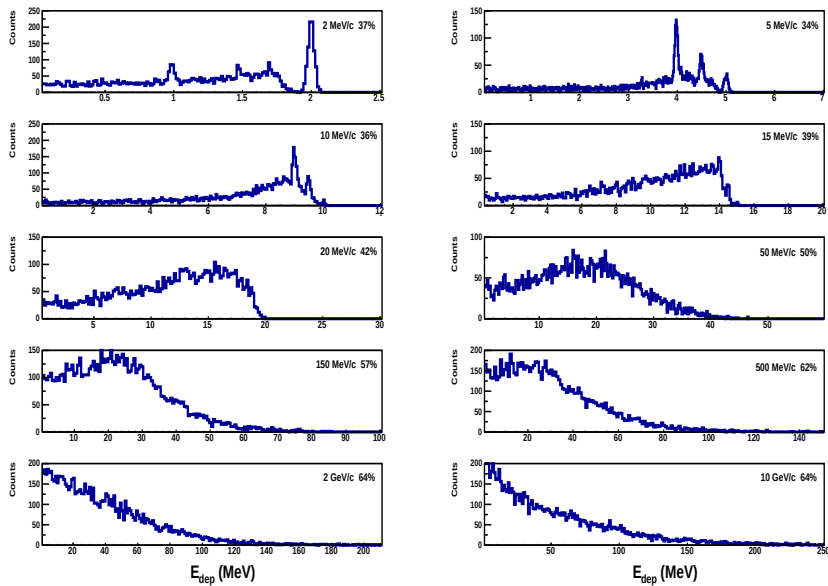


Figure G.7.: CsI(Na) bare crystal. Energy deposited spectra at different initial momentum. Incident particles: γ -rays.

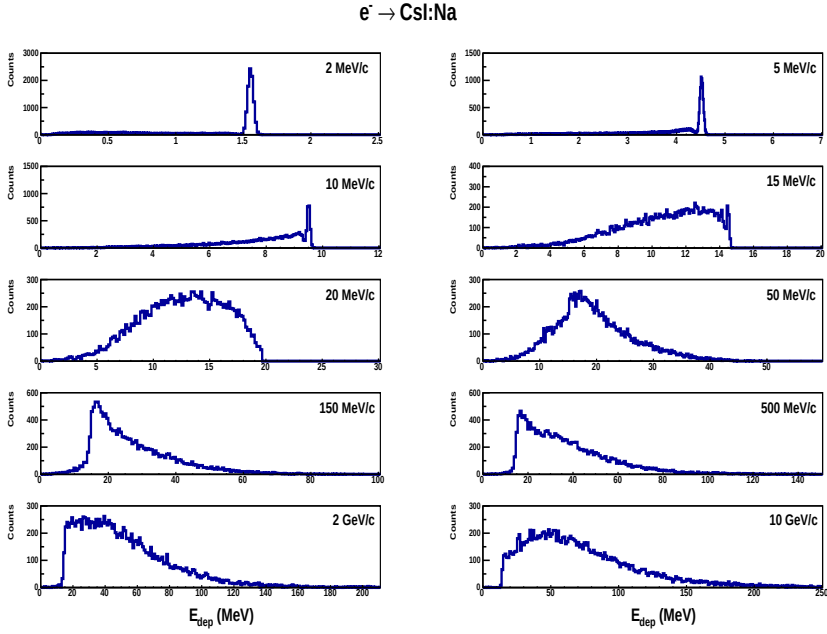


Figure G.8.: CsI(Na) bare crystal. Energy deposited spectra at different initial momentum. Incident particles: e^- .

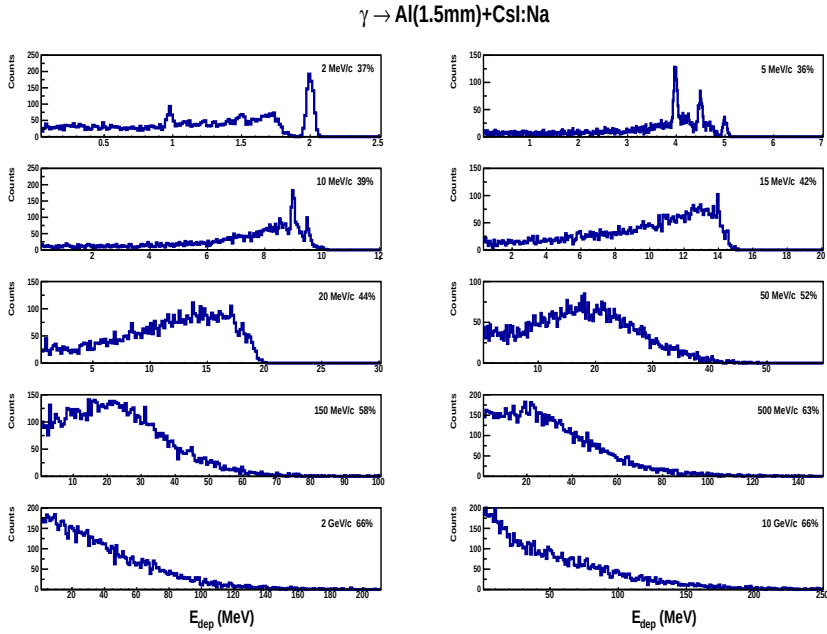


Figure G.9.: CsI(Na) bare crystal+Al foil 1.5 mm. Energy deposited spectra at different initial momentum. Incident particles: γ -rays.

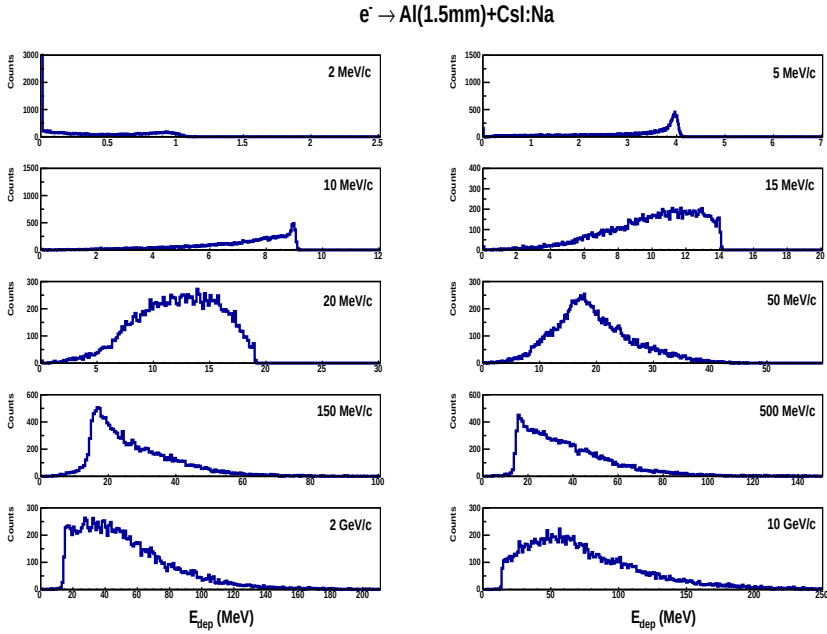


Figure G.10.: CsI(Na) bare crystal+Al foil 1.5 mm. Energy deposited spectra at different initial momentum. Incident particles: e^- .

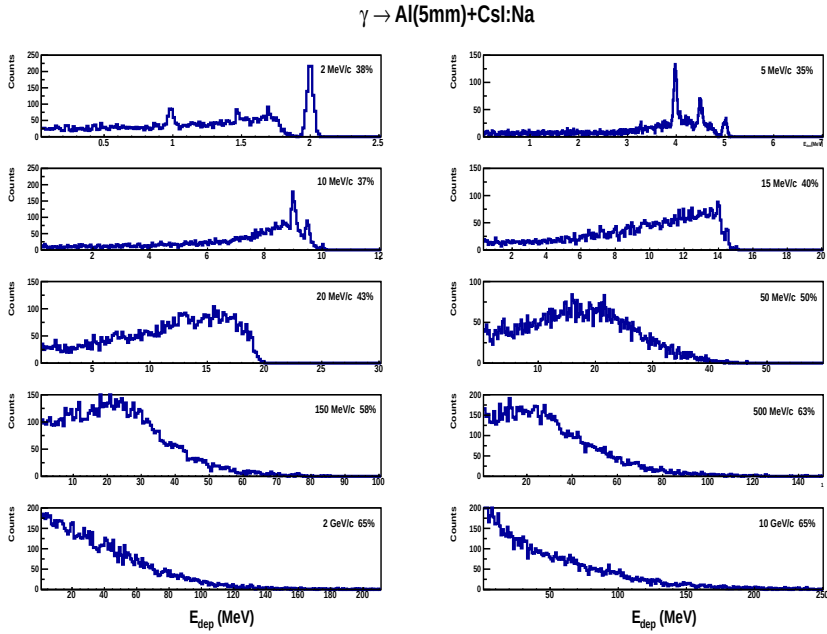


Figure G.11.: CsI(Na) bare crystal+Al foil 5 mm. Energy deposited spectra at different initial momentum. Incident particles: γ -rays.

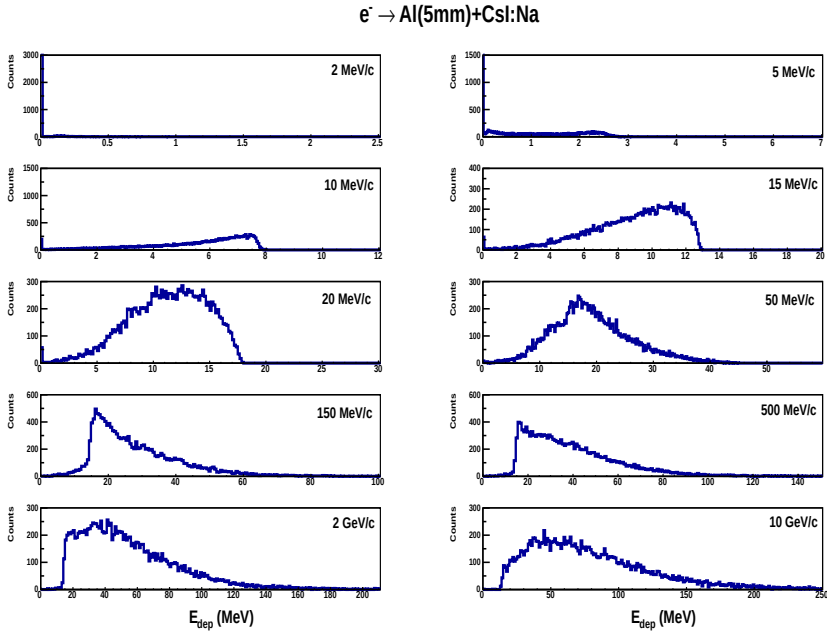


Figure G.12.: CsI(Na) bare crystal+ Al foil 5 mm. Energy deposited spectra at different initial momentum. Incident particles: e^- .

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