Identification of ions by pulse-shape analysis & evaluation of Lyso scintillator crystal

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Abstract

Radiation detection and identification of ions has always been an issue in subatomic physics. Depending on charge and mass ions interact differently with matter, as described in the Bethe-Bloch formula, and therefore the deposited energy per unit length varies. Different approaches can be used to separate these ions by studying the pulse-shape from a silicon detector. In this thesis the use of a neural network, rise time and wavelet have been investigated. In most cases these methods were successful in separating between the ions. The data used in the analysis originates from two experiments at Centro Nacional de Aceleradores - CNA, in Seville 2007 and 2008.

 γ -radiation is of great importance in understanding the underlying structure of nuclei. Photons interact with matter in three ways: photoelectric absorption, Compton scattering and pair production. Because photons are more likely to interact with matter with high Z number it is favorable to use dense detector material. In this thesis we use a Lyso crystal which partially consist of 176 Lu. Since this crystal has not been tested thoroughly we want to find out if it can be used for, e.g. detection of positronium annihilation. After experiments with different setups we can conclude that it will be difficult to separate these photons from the self-radiation of the crystal just by looking at the deposited energy.

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1 Introduction

The fundamental understanding of basic building blocks in our world depends on our ability to measure different types of radiation. At the turn of the 20th century α -, β - and γ -radiation was discovered. Since then, numerous experiments has increased our knowledge in particle physics. To further improve the understanding, the invention of new and better methods for radiation detection is of great importance.

One way to detect ions is to use ΔE -E detectors. The setup consists of two parts. A thin detector which the ion can pass through leaving a part of its energy. A second, thicker detector, where the ion stops and transmits the rest of its energy. By analysing the energies deposited in the two detectors the ion species can be established. Although this kind of setup is very accurate and commonly used some disadvantages exist. It fails at energies below 2 MeV/u, mainly because the ions can not pass the thin detector due to lack of energy [1].

The distance the ion travels before it has deposit its energy, in e.g. a silicon detector, is dependent of charge and mass. This has been known for a long time, both from experimental research and theoretical calculations such as the Bethe-Bloch formula. Therefore the ability to separate ions by just one detector is theoretically possible and crucial for this thesis.

In most nuclear reactions the final nucleus is left in an excited state which often decays towards the groundstate by emitting γ -photons. Since these photons contain information about the structure and composition of the nucleus the detection is of great importance.

Positrons are created in nuclear reactions such as pair production and β^+ -decay. Due to the Coulomb force positrons and electrons attract each other and annihilates by emitting two γ -photons in opposite directions, each with the energy 511 keV. In most cases positrons can not be detected directly due to this annihilation process. The option is to study decay products, e.g. γ -photons.

In this thesis we will describe and use a scintillator crystal detector which has short stopping length for γ -radiation because of its dense building materials. This makes the crystal a good candidate in future experiments for γ -detection.

2 Semiconductor detectors

2.1 Purpose

The main purpose is to investigate if it is possible to identify ions by studying the shape of the pulse from a silicon detector and, if so, find algorithms for this. To do this we would like to:

- study the interaction between ions and matter
- gain insight in contemporary methods to detect ions
- study how silicon detectors of various thickness effects the shape of the output signal

• use algorithms on experimental data with the aim to differentiate ions

2.2 Theory

2.2.1 Interactions with ions

When ions pass through matter they will interact with atoms and lose energy, mainly through inelastic collisions with electrons. These collisions are divided into two groups: soft collisions and hard collisions. In the first group only an excitation results, and in the latter, enough energy is transferred to ionise the atom. To predict how far the particles travel in matter it is useful to have the average energy loss per unit length. Niels Bohr was the first to calculate this quantity, called the stopping power $\frac{dE}{dx}$, using classical arguments. Later Hans Bethe and Felix Bloch used quantum mechanics to calculate the stopping power expressed as momentum transfer between the particles. The formula [2] is given by

$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[ln \left(\frac{2m_e \gamma^2 v^2 W_{max}}{I^2} \right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right]$$
(1)

with $2\pi N_a r_e^2 m_e c^2 = 0.1535 \,\mathrm{MeV} \,\mathrm{cm}^2/\mathrm{g}$

$$\begin{split} r_e: \text{classical electron radius} &= 2.817 \times 10^{-13} \, \text{cm} \\ m_e: \text{electron mass} \\ N_a: \text{Avogadro's number} \\ \text{I}: \text{mean excitation potential} \\ \text{Z}: \text{atomic number of absorbing material} \\ \text{A}: \text{atomic weight of absorbing material} \\ \rho: \text{density of absorbing material} \\ z: \text{charge of incident particle in units of e} \\ \beta &= \frac{v}{c} \text{ of the incident particle} \\ \gamma &= \frac{1}{\sqrt{1-\beta^2}} \\ \delta: \text{density correction} \\ \text{C}: \text{shell correction} \end{split}$$

 W_{max} : maximum energy transfer in a single collision

The electrons of the detector material are bound to atoms with an orbital frequency ν . The mean excitation potential, I, is the orbital frequency averaged over all bound electron states, $\bar{\nu}$, times Planck's constant, h. Values of I have been found for several materials by measuring $\frac{dE}{dx}$. The first two terms in equation (1) come from the quantum mechanichal calculation and the two later are corrections. The addition of the density correction, δ , is a result of the electric field of the particle polarizing the atoms along its path. Electrons far from this path will be shielded from the full electric field intensity. If the particle was to collide with these outer lying electrons it would contribute less to the total energy loss in the original Bethe-Bloch formula. Since there is a connection between this effect and the density of the material the name density correction

follows. For equation (1) to hold, the velocity of the incident particle must be much greater than the orbital velocity of the electron. If this assumption fails the Bethe-Bloch formula breaks down. To prevent this the shell correction, C, was introduced. [2]

An integration over all energies results in the distance a particle travels before it has lost all its energy. The formula is only valid for charged particles much heavier than electrons as lighter ones are effected by additional reactions.

According to Bethe-Bloch formula higher Z numbers result in shorter stopping distances which are preferable in a detector. However, with higher Z numbers backscattering increases.

2.2.2 Semiconductors

Naturally silicon and germanium have four valence electrons which form covalent bonds. Therefore all electrons are bound to other atoms and creates a band which is called the valence band. The next energy level, permitted for the electrons to excite to, is called the conduction band. The space between these two bands is a forbidden zone, called the band gap. The band gap determines if a material will be a metal, a semiconductor or an insulator, figure 1. In a metal the valance band will extend over and cover a part of the conduction band and therefore the energy needed to excite one electron will be practically nothing. In an insulator the width of the band gap will be so wide that practicly no electrons will overcome it. In semiconductors the band gap will be low, but still exist and therefore stop electrons to flow freely from one band to another. [3][4]

2.2.3 Doping

In semiconductors the energy needed to excite an electron can be manipulated with the addition of impurities. This is called doping. For example, silicon has four valence electrons which can be doped by adding an atom with five valence electrons. Four electrons from the added atom will then bind to the four valence electrons in silicon. The fifth will create a new energy level just beneath the conduction band. This kind of doping is called n-doping, because of the addition of an extra electron to the material. The opposite, p-doping, is achieved by adding an atom with three valence electrons. The electron in silicon, which will have no electron to bind to, will create an energy level just over the valance band. These two kinds of doping both introduce new energy levels which lowers the energy needed to excite an electron.[3][4]

2.2.4 Diodes

When a p-doped and a n-doped material are put together they create a diode. The surplus of electrons from the n-doped material diffuse into the p-doped and the holes from the p-doped material diffuse into the n-doped. This creates a space between the two materials which is denominated the depleted area. In this process electrons and holes create an electric field within the material. By applying reverse bias voltage this field can be extended to the entire diode which. [3][4]



Figure 1: Schematics over band gaps

2.2.5 Radiation detection with a semiconductor detector

A semiconductor detector is made of a diode with applied reversed bias voltage. When ions enter the detector they collide with electrons, excite them, and create electron-hole pairs. These electron-hole pairs will be attracted by the applied voltage and flow in opposite directions, i.e. an electrical current has occurred which can be transferred to an analysing equipment. [2][5]

Silicon and germanium are the two most commonly used semiconducting materials for radiation detection. The advantage with germanium is a higher Z number which results in a short stopping distance. The disadvantages however are that it has to be operated at low temperatures and higher Z number increase backscattering. Therefore germanium is mainly used for γ -detection while silicon is used for ion detection.

2.2.6 Preamplifier

The signal from the detector is transferred to a preamplifier whose main task is to enhance the output signal and convert the current pulse to a voltage pulse. The preamplifier splits the signal into two components. One component is enhanced, called the T-signal, and one is both integrated through a capacitor and enhanced, called the E-signal, figure 2 and 3. The T-signal is fast and gives an more accurate shape of the current pulse. In contrast the E-signal is slow but its amplitude is proportional to the energy of the pulse. To minimize noise, the preamplifier is closely coupled to the detector. [5] [2]

2.2.7 Wavelets

The intention of this section is to give an insight into how wavelets work and why the use of wavelets in data analysis is of interest.

A wavelet transform can roughly be thought of as a Fourier transform but with different base functions. However, there are some major differences. The Fourier transformation uses an amplitude-frequency domain while the wavelet transform uses a time-scale domain which has the advantage that it can detect



Figure 2: T-signal

Figure 3: E-signal

small discontinuities in a signal. This because the signal is transformed in different scales. A Fourier analysis divide the signal into different frequencies while the wavelet transform divide the signal into shifted and scaled versions of the so called Mother wavelet. A wavelet have the following property:

$$\int_{-\infty}^{\infty} \psi(t)dt = 0 \tag{2}$$

A family of wavelets is created by scaling ψ by s and translate it with u, equation (3).

$$\psi_{u,s}(t) = \frac{1}{\sqrt{s}}\psi(\frac{t-u}{s}) \tag{3}$$

The wavelet transform of $f \in \mathbf{L}^2$ at time t and with scale s, equation (4)

$$Wf(u,s) = \int_{-\infty}^{\infty} f(t) \frac{1}{\sqrt{s}} \psi^*(\frac{t-u}{s}) dt$$
(4)

According to [13] ψ is the transfer function of a bandpass filter. This can be seen by rewriting the wavelet transform as a convolution.

There exist three different types of wavelet transforms: The continuous, the discrete and the semi discrete. Since we only have been working with discrete wavelet transforms (DWT) these are described more precisely.

When computing the DWT instead of a bandpass filter, a high and a low pass filter are used which the signal is processed through. This is still a transformation but in terms of filters. The two filters are correlated with a filter called the quadrature mirror filter, which is roughly a filter that divide the signal into two bands. The coefficient of the filter is calculated as

$$y[n] = (x * h)[n] = \sum_{k=-\infty}^{\infty} x[k]h[n-k]$$
 (5)

$$y[n] = (x * g)[n] = \sum_{k=-\infty}^{\infty} x[k]g[n-k]$$
 (6)

Note that we have used Mallats, [13] syntax which means that g denotes the high pass filter and gives the detailed coefficient while h denotes the low pass filter

and gives the approximate coefficients. The coefficients passing through the high pass filter are usually called detailed coefficients. Since we have removed half the frequencies, we can according to Nyqvist theorem downsample the signal with a factor 2. Each decomposition halves the time resolution by a factor 2.

The wavelet used in this report is a db1 (Daubechies 1) which is the first of a family of wavelets. This transform has a, so called, Father wavelet which scales the function and generates the orthogonal multiresolution analysis.

$$y_{\text{low}}[n] = \sum_{k=-\infty}^{\infty} x[k]h[2n-k]$$
(7)

$$y_{\text{high}}[n] = \sum_{k=-\infty}^{\infty} x[k]g[2n-k]$$
(8)

In figure 4 we can see a graphic representation of the levels of decomposition.



Figure 4: A schematic description of the decomposition of the signal

2.3 Method

2.3.1 Experiments

Seville 2007 The data used in this thesis originates from an experiment in Seville. The experiment took place at Centro Nacional de Aceleradores - CNA, February 5-9 2007, and was performed by a Spanish group from the University of Huelva and an Italian group. The goal was to optimize equipment to achieve pulses which hopefully could be separated using pulse-shape analysis.

The accelerator in Seville is a tandem accelerator with a maximum tension of 3 MV. To extract the desired isotope and energy a dipole magnet was used to deflect the beam by 90°. To decrease the intensity of the beam before hitting the detector a thin metal foil was used to scatter some of the ions. The detector used was a neutron-doped silicon detector which was connected to a fast Italianmade preamplifier. To save the data an oscilloscope of type LeCroy WavePro 7000 A Series was used. The setup was used to accelerate p, d, α , ⁶Li and ⁷Li to energies between 4 and 12 MeV. [1]

Seville 2008 The experiment of this year took place at Centro Nacional de Aceleradores - CNA, Seville. The aim was to study how silicon detectors of various thickness effects the shape of the output signal and to get data from the ions ⁶Li, ⁷Li, ⁹B, ¹⁰B, ¹²C and ¹³C. These ions were accelerated to energies between 6 and 20 MeV.

The experimental setup and procedure was the same as last year, with some exceptions. This year the setup consisted of four detectors placed in a circle with the beam in the center, figure 6. A piece of gold foil was used to scatter the ions to decrease the intensity of the beam, figure 5. The four detectors were all silicon based neutron-doped with different thickness: 17, 50, 75 and 500 μ m.



Figure 5: The setup viewed from the side Figure 6: The setup viewed from the front



Figure 7: Accelerator in Seville

2.3.2 Neural networks

The aim of the data analysis was to separate the particles based on their pulseshape. Previous work on this subject [1] came to the conclusion that it was not possible to separate different nuclei using risetime and amplitude. A decision was therefore made to look at multiple parameters and to find the best combination of them. The parameters chosen do not necessarily have any physical interpretation. The use of neural networks is favorable for this kind of problems. It combines multiple parameters in solving complex problems where no absolute parameters exist.

A neural network is built up by a number of layers, each containing a number of neurons. Each neuron calculates the dot product of its weight vector and the input vector. The resulting scalar is an element of the input vector to the next layer. For example, in figure 8, the input vector to the neuron with the weight vector $\begin{bmatrix} E \\ F \end{bmatrix}$ is $\begin{bmatrix} C & D \end{bmatrix}$. The resulting dot product is H. To get the weights correct the network has to be trained. This is done by sending



Figure 8: Neural network with one hidden layer

input data to the network and defining the output. The neural network then modifies its scaling vectors using a method called "back propagation" [11].

We chose to have a number of output neurons equal to the number of ions to distinguish between, so that each output neuron represent one type of ion. When sending a particle to the network we want the corresponding output neuron to return "1" and all the others "0", figure 9.

The neural network approach was divided into three parts. In the first step we wanted to train the network to separate ⁴He, ⁶Li and ⁷Li, all of the same energy. As a second step, the test was expanded to include several energies and train the network on all of them. In the final step we trained the wetwork on data from some energies and tried to apply this network on energies that we did not train on. If successful, the network would hopefully separate the particles based on the shape of the signals.

2.3.3 Wavelets

One approach was to look at the frequency spectrum as in speech recognition. This idea was abandoned after realising that the T-signal is almost a peak in the time spectrum. A peak in the time domain is represented by all frequencies in the frequency domain. This results in variations which are easier to detect in the time domain rather than in the frequency domain. This led to the idea to analyse the signal using wavelets.

Figure 13 shows how the signal can be separated by looking at the most significant coefficient. The plot is obtained by transforming the T-signal and Esignal to the time-scale domain using a db1 function and then plotting the sum of the four most significant coefficients from both signals against each other. The signal is normalised in the time domain, so that it shall only differ depending on



Figure 9: Optimal output from neural network

the shape of the pulse and not the amplitude. The program is written in Matlab using the SWT (stationary wavelet transform), which is a type of DWT. The difference in this application is not essential and the theory behind DWT is described in section 2.2.7.

2.3.4 Noise reduction

In order to extract information from the signal it is preferable that the signal originates from the interaction between the ion and the detector. However, there is usually an uncertainty whether the information comes from noise or from interaction with the detector.

When observing the T-signal, figure 2, there is noise but it also seems to be another signal with some periodicity. This periodic signal and the signal of interest seems to be superpositioned and therefore effects the amplitude and shape of the pulse. Even when the peak is dominating, the uncertainty of parameters increases. The amplitude of the periodic noise is of magnitude 10 percent of the signal. Since the phase of the periodic noise changes, it results in an uncertainty up to 20 percent of the amplitude. In order to remove noise a Fourier transformation, using the Matlab provided fft (fast Fourier transformation) routine, is used. In the frequency domain, the peak corresponding to periodic noise around 10 MHz, see figure 10, is removed. The signal is transformed back to the time domain using the ifft function (inverse fast Fourier transform).

In order to reduce non-periodic noise it is beneficial to use wavelets. Wavelets do not affect the sharpness of the signal nearly as much as a moving average or a high frequency filter [12]. The method is implemented using Matlabs SWT with a db1 wavelet. A threshold was used to set the small coefficient to zero. Then the signal was transformed back to the time domain using iswt (inverse stationary wavelet transform).



Figure 10: The frequency spectrum of a ⁷Li 9 MeV T-signal

2.3.5 Rise time

A more physical way of approaching the problem is to look at expected differences between the ions. More precisely how the pulse-shape should differ depending on which particle hit the detector. These differences originates in how the particle interact with the detector as described in section 2.2. This gives the idea that a more charged particle should interact faster with the detector which leads to a faster rise time. This method was investigated in [1]. The result were not conclusive but some trends were observed.

In order to investigate how the rise time depends on the energy and the ion, a program was written and implemented in Matlab. This program calculated the time it took for the signal to rise from 10 to 90 percent of the maximum value and also the amplitude itself. The program was used to analyse the E-signal directly as done in [1]. The T-signal was integrated giving a new E-signal which was analysed.

2.4 Results

2.4.1 Seville experiment 2008

The data received from the Seville experiment of this year was analysed using the same methods and algorithms described previously. When analysing this new data, we encountered several problems. The data received only included the 8 MeV energy measurements and therefore we could not fully evaluate our neural network approach.

The neural network was used to separate isotopes of 8 MeV energy, but did not result in a 100 percent accuracy. We believe that this problem resulted from the data only attaining a small number, ~ 100 , of discrete values. There was not enough information left in the received data for the neural network to distinguish between. Another problem encountered using the rise time approach was that in some signals a step-function appeared. Since we can not explain these discontinuities, we can not remove this data. This means that the rise time approach fails to separate the ions.

2.4.2 Neural networks

In the first step, using just a few basic parameters we were successful in separating all the ions. We used the same parameters in the second step, and were able to identify the ions in about 70 percent of the cases. We needed to find more shape-specific parameters. Therefore we had to look for parameters which are energy independent but specific for each ion.

We decided to choose parameters based on:

- A small separation in parameters for ions of the same type and energy
- A large separation in parameters for different ions
- A small separation in parameters for ions of the same type but with different energies

Our strategy was to study histograms of the parameters and try to get each ion in a Gaussian shaped peak separated from the other ions. We ended up with 18 parameters, nine for the T-signal, eight for the E-signal and one from the wavelet transformation. With these new parameters we were able to separate 100 percent of the ions for multiple energies.

When using these parameters in the third step it did not produce satisfying results. We learned that it was hard to tell which parameters would give a good result. Even parameters not having Gaussian shaped distribution could still contribute to a good result.

To give the neural network as good data as possible we took 200 points directly from the signal, moved the baseline to zero, and sent it to the network, figure 11.



Figure 11: The points used to train the network

With these data the network correctly separated 84.93 percent of the total amount of ions, figure 12. Some energy-ion combination have been problematic throughout the whole analysis and many times have their correctness been questioned. These ions are ⁶Li at 9 and 11 MeV and ⁴He at 4 MeV. They are among the problematic ones here as well which can be seen in figure 12.



Figure 12: The result produced by the neural network

2.4.3 Separation of ions using wavelets

Figure 13 is obtained by the method described in section 2.3.3 and clearly shows the strength in wavelet analysis.



Figure 13: The sum of the most significant coefficient from the T-signal plotted against the most significant coefficients from the E-signal. The blue colour represent ⁴He with energy levels 4-9 MeV, yellow ⁶Li energy levels 7-12 MeV, red ⁷Li energy levels 7-12 MeV.

2.4.4 Noise reduced signals

The Fourier transform of a T-signal, figure 10, has a peak near 10 MHz. Empirical studies of our signals show that the periodic noise mainly consist of this frequency. When this peak is removed and the signal is transformed back to the time domain we obtain a signal as in figure 14(b).



(b) After removing a top around 10 MHz in the frequency spectrum



(c) After de-noising (b) using wavelets

Figure 14:

2.4.5 Separation of ions using rise time

The idea in "Studies of pulse shapes from semiconductor detectors" [1] was to study the rise time defined as the time it took for the E-signal to rise from 10 to

90 percent of the maximum amplitude. The rise time as a function of amplitude for different ions is observed in figure 15(a).



(a) The rise time as a function of amplitude from the E-signal



(b) The rise time as a function of amplitude from the integrated T-signal

Figure 15: The blue colour represent 4 He with energy levels 6-9 MeV, yellow 6 Li energy levels 7-10 MeV and 12 MeV, red 7 Li energy levels 8-12 MeV.

The rise time seems to be independent of the amplitude. Instead, an amplitude distribution within each energy is observed. However, the relation between higher amplitude and longer rise time is not apparent. This leads to the idea that some information is lost in the process of creating the E-signal. In figure 15(b) the integrated T-signal is plotted as in figure 15(a).

When comparing these two plots, the degree of separation is similar but the integrated T-signal is more in line with theory. Apparently, it is possible to draw lines in the rise time-amplitude scale between the different ion types. Such lines would separate most of the ion species from the data obtained in Seville 2007. These lines would also give us a prediction to ions with other energy levels than in the experiment. Note that the 11 MeV for ⁶Li is removed since it does not

follow the same distribution pattern as for other energy levels and is therefore assumed to be incorrect.

2.5 Discussion

2.5.1 Neural network

The neural network approach was quite successfull. A simple network, coupled with just a few parameters, did recognise the majority of the ions. This illustrates the strenght of neural networks which also have some disadvantages. In training networks, one need to be certain that the training data is correct. One set of corrupt parameters would have great consequences for the performance of the network. The neural network has a life of its own and might find differences that it was not supposed to find. If one measurement has a slight offset or just a different kind of noise, the network might use this information in its calculations. The major advantage in using a lot of points from the signal as parameters, is that no information is lost by choosing wrong parameters. The disadvantage against a few well chosen parameters is that more time is needed to train the network.

The result hopefully reflects the shape of the signal itself and is independent of how the data was acquired. To be certain one would need to have data for multiple ions and energies taken under unchanged conditions. Questions has been raised about the reliability of the data from the Seville experiment 2007. The experiment of this year was conducted to obtain more reliable data. Unfortunately the data received from this experiment could not be used to train and test a neural network.

2.5.2 Wavelets

Wavelets have a lot of interesting properties that makes them useful for data analysis. Although, in order to use them it would be necessary to have more data for different particles and energy levels.

This approach, although successful in separating the ion of interest, is without any predictions. We can only show that a separation of ions is obtained using this specific data. In the case of ions with another energy or just a new experimental setup, this method could fail. In order to use wavelets to separate ions a more profound mathematical analyse is necessary.

2.5.3 Rise time and noise reduction

In order to get a higher degree of separation between the ions, it is crucial to have a good detector and a fast preamplifier. Otherwise important information is lost during the process in amplifying the signal. While trying to determine the time it takes for the ion to deposit most of its energy it seems to be more advantageous to look at the integrated T-signal instead of looking directly at the E-signal. The rise time of the E-signal in the 2007 experiment in Seville seems to be rather independent of the ion, and is therefore not very helpful in the rise time approach. Why the information is lost, in creating the E-signal, is not probed in this thesis but is crucial if the E-signal should be used to separate ions. Since information is lost in the process of creating the E-signal there are probably also information lost when the signal is amplified into the T-signal.

3 Scintillator detectors

3.1 Purpose

The Lyso crystal is a new type of scintillator material and our main purpose is therefore to get better knowledge of its advantages, disadvantages, how the setup should be, what kind of output it gives and how this should be analysed. To do this we need to:

- gain knowledge of this type of detectors
- study the interaction between photons and matter
- perform experiments with the Lyso crystal and analyse the output

3.2 Theory

3.2.1 Interaction with photons

Photons differ from ions in their interactions as they have no charge or mass. Therefore they can not interact through inelastic collisions with atomic electons. This explains why γ -rays penetrate deeper into matter than ions do and why a beam of photons changes in intensity but not in energy when it passes through a target. The attenuation of the photon beam is exponential and can be described as in (9).

$$I(x) = I_0 \exp(-\mu x) \tag{9}$$

 I_0 is the incident beam intensity, x is the thickness of the absorber and μ is the absorption coefficient. The photons interact through the photoelectric effect, Compton scattering and pair production where the relative probability depends on the Z of the matter and the energy of the photons.

Photoelectric absorption This is the dominant interaction for low energy photons, close to the binding energy of electrons. As the dependence goes as Z^5 the interacting matter is also very important[2]. In the reaction the photon is absorbed by an atomic electron, the energy not used to break the binding is transformed into kinetic energy. To conserve the momentum the recoil has to be absorbed by a nucleus. This is why the reaction can not occur on free electrons.

Compton scattering This is the scattering of photons against free electrons. In matter the electrons are bound, but when the photon energy is much higher then the binding energy it is a good approximation. In the process the photon transfer some of its energy to the electron. Typically this process is dominating at lower Z and in the middle range of energy from about 0.25-7 MeV [5].

Pair production A photon can in the presence of a nucleus convert into an electron and a positron. Similar to the photoelectric effect the nucleus is needed to conserve the momentum. In theory the photon only need 1.022 MeV to create a pair but in practice it will not show in the spectrum until the photons have an energy of a few MeV.

3.2.2 Lambert's cosine law

A Lambertian surface is a flat emitting area. The radiation will, with this approximation, be most intense normal to the surface and diminish to zero at a 90° angle as $\cos \phi$ according to Lambert's cosine law [7]. In other words, at a right angle an observer covering the area dA_0 and the solid angle $d\Omega_0$ will detect the intensity:

$$I_0 = \frac{IdAd\Omega}{dA_0 d\Omega_0} \tag{10}$$

This is from a radiating surface dA big and subtending a solid angle $d\Omega$. The solid angle is measured from an observers point of view. It corresponds to the part of an imagined sphere, originating from the observer, the object measured covers.

3.2.3 Scintillator detectors

Some materials give off a flash of visible light when struck by a particle or radiation. Those who are transparent to this light, have a short decay constant and a high conversion rate of energy to light can be used as detectors. The scintillator detectors are usually divided into groups, depending on what material they consist of. The groups are: organic crystals including organic liquids and plastics, gaseous, glasses and inorganic crystals. All having slightly different abilities and applications.

The scintillator detctors have some great advantages compared to other detectors. They are in general, above a certain limit, linearly dependent on the incoming energy. They have a fast response and recovery time and in the cases where the material has more then one scintillation mechanism, pulse-shape discrimination can be used to distinguish the particles.

3.2.4 Photomultipliers

A photomultiplier transform light signals into electric signals [2]. It has a photosensitive window were a photon will knock out an electron. Behind the window there is a dynode with an applied voltage that will accelerate the electron towards it. The electron hits the dynode and knock out secondary electrons and they are all accelerated toward a second dynode with a higher potential as can be seen in figure 16. The process continues and an electron cascade is created. In the end they are all collected in an anode which gives an electric pulse.



Figure 16: Schematic picture of a photomultiplier.



Figure 17: Lyso scintillator crystal



Figure 18: H8500 photomultiplier

3.3 Method

3.3.1 Material

Lyso scintillator crystal The crystal used is made out of $Lu_{1.8}Y_{.2}SiO_5$ and doped with cerium. It is $48.74 \times 48.87 \times 31.28$ mm and divided into 12×12 smaller crystals with a pocket of air in between them. The decay time is 41 ns. Lutetium has a radioactive component, ¹⁷⁶Lu, with a half-time of 3.8×10^{10} years [8]. It β -decays, mainly to ¹⁷⁶Hf in an excited state of 596.82 keV. This state decays to two more states before reaching the ground state emitting three γ -rays with energies of 307, 202 and 88 keV.

H8500 photomultiplier and frontpanel The H8500 is a flat panel photomultiplier divided into 8×8 anodes for 2D-imaging. In total it spans 49.26×48.79 mm. It operates on supply voltages down to -1100 V and has a maximum output of 2 V with a rise time of 0.8 ns. The manufacturer supplies a calibration scheme measured with a supply voltage of -1000 V. The photomultiplier returns all anode voltages as well as the summed dynode voltage. [9]

The frontpanel for the H8500 photomultiplier collects all the anodechannels and sums them up to four signals A, B, C and D corresponding to the corners of the photomultiplier. It is fitted with a 16-pin ffc connector and requires ± 5 V and 6 V supply voltage in three of the pins. The output signals are $\pm (B + C)$, $\pm (A + D)$, $\pm (C + D)$ and $\pm (A + B)$. [10]

3.3.2 Self-radiation measurements

To measure the intensity of the self-radiation in the Lyso crystal a cylindrical germanium detector of diameter 59.5 mm was used.

The crystal was put in a tube together with a ¹³³Ba sample and surrounded by lead. The sample was approximated with a point source radiating with 18.471 kBq and the detector was assumed to be a Lambertian surface. The solid angles for the detector and the Lyso crystal in relation to each other was determined.

The 133 Ba sample has peaks at 81 keV, 276 keV and 303 keV [14] that are suitable for comparison with the radiation from the Lyso crystal. Measurements were taken both with the front and with one of the sides turned towards the germanium detector.



Figure 19: Scatterplot of half the detector

3.3.3 Setup of scintillator detector

The Lyso crystal is wrapped up in tape on three sides to protect it from impact and light. The fourth, open side shows the front side of the 12×12 crystals and it was coupled by an optical plate to a H8500 photomultiplier.

The photomultiplier was coupled to a H8500 frontpanel which was connected to a CAMAC standard front panel by coaxial cables. That in turn connected the four output signals to the LeCroy WavePro 7000A digital oscilloscope. For the supply voltage a Voltcraft PS2403Pro voltmeter was used. As both the crystal and the photomultiplier are very sensitive to radiation they were screened from radiation by blocks of lead and isolated from visible light by a cardboard box and foam rubber.

Measurements were done with and without samples of ²²Na and ⁶⁰Co placed underneath and by the side of the crystal.

3.4 Results

3.4.1 Radiation from the Lyso crystal

The two peaks at 202 keV and 307 keV from 176 Lu shows in the spectrum. The front of the Lyso crystal was radiating with $0.8 - 1.4 \text{ kBq/m}^2$ and the side with $0.30 - 0.58 \text{ kBq/m}^2$. The histograms can be seen in figure 23 and 24.

3.4.2 Detection with the scintillator detector setup

The 64 anodes of the multiplier each detects in a distinct area that can clearly be seen in the XY-scatterplot, figure 19. The data comes from a calibration measurment made on separate anodes with the other 63 covered by tinfoil. Most of the detection is made in the middle of the anodes while towards the edges few photons are discovered.

The anodes ability to discover the γ -rays shows a Gaussian distribution depending on the amplification. In figure 20 the histogram for one of them can be seen. Most γ -rays are discovered in the middle and the ability decline to practically nothing at the edges. The amplification also varies in between the different anodes as is shown in figure 21 and 22.



Figure 20: Scatterplot of half the detector

With a higher supply voltage than 750 V there is a problem with flashovers in the photomultiplier. This creates a problem because the calibration measurements supplied with the H8500 photomultiplier do not translate directly to lower voltages. The hits in the low amplifying, outer parts, of the anodes can only be explained by high energy particles, such as muons 19.

The Lyso crystal is very fast, especially for an inorganic crystal, and the photomultiplier has a fast response time. The limitation in this setup is the oscilloscope that is not able to trigger on all pulses.



80 70 60 50 40 30 20 10 0 100 110 120 130 140 150 160 170 180 190 200

Figure 21: A histogram of the output from part of the anodes showing the varying am- Figure 22: The same histogram as in 21, plification

as seen from above

Discussion 3.5

Self-absorption in the Lyso crystal 3.5.1

The radiation of the crystal does not create a problem as the photomultiplier is sensitive only for photons in the visible spectra. A bigger problem is the selfabsorption that creates signals competing with the ones we want to detect. The front of the detector gave of $0.8 - 1.4 \text{ kBq/m}^2$ and the side $0.30 - 0.58 \text{ kBq/m}^2$. When using Lambert's cosine law for the radiation we assumed radiation only from the surface of the crystal. If this was correct the radiation/surface area should be equal for the front and the side. In fact the γ -rays are penetrating



the Lyso crystal and a ¹³³Ba source. The the Lyso crystal and a ¹³³Ba source. The Lu peaks are clearly seen at 202 keV and Lu peaks are clearly seen at 202 keV and $307 \,\mathrm{keV}$.

Figure 23: Radiation from the front of Figure 24: Radiation from the side of $307 \, \mathrm{keV}$.

from inside the crystal and the greater depth seen from the side compared with the front should give radiation with higher intensity. Our measurements show the opposite which indicates a significant absorption inside the crystal.

Energy measurement 3.5.2

We have been unable to determine the energy for incoming radiation in a reliable manner. The Gaussian distribution of the amplification, as well as the variation between the anodes, made it impossible to measure energy from the amplitude or integral of the pulses.

3.5.3**2D-detection**

The Lyso detector has a good ability to determine the position of an incoming photon as seen in figure 19. The problem is to distinguish incoming γ -rays from the self-produced. Energy determination would be the natural method but has proven problematic. Even if the energy for the particles could be determined there still is a problem to separate them from the self-absorbed γ -rays. Those have energies of 307, 202 and 88 keV that combined gives a peak at 597 keV. One of the suggested applications for the Lyso crystal is to determine the position of positronium annihilation. To find the γ -rays emitted by the annihilation in the energy spectrum among the signals from ¹⁷⁶Lu is hard. Another approach would be to have crystals on opposite sides of the reaction and detect both of the signals. With a strict coincidence condition the 511 keV γ -rays should be dominant in the output.

Conclusion and outlook 4

Semiconductor detector After working with data from the experiment in Seville 2007 we can conclude that there really are differences in the pulse-shape between different ion interactions. A conclusion can not always be made from the signal in terms of which ion that hit the detector, neither with the use of neural network, integrated T-signal or wavelets. This is mainly because we get a distribution of shapes within each ion species and these distributions are often overlapping. It is to some degree possible to minimise the overlap by use of noise reduction algorithms, although the evasion of overlap has been shown impossible. It is possible that too much of the information is lost when the signal is amplified in the preamplifier to be able to separate all the events. One advantage with the integrated T-signal, even if it can not separate all ion species, is the possibility to define values that can come from two or more different ion types. This results in a lower efficiency, since we can not conclude what type of ion is causing the event. Even though this is not ideal it is preferable compared to identification errors.

One interesting way to continue with this project would not only be to do more experiments in order to collect more data, but also to make a simulation of the interaction between ions and the silicon detector. One idea is to simulate this in GEANT 4 which is a C++ library, developed at CERN, and commonly used for simulations in particle physics.

Scintillator detector The Lyso crystal has some great advantages in its quick response and large light output. The division into 12×12 one crystals makes it possible to determine a 2D position with good accuracy as in figure 19. The problem consists of determining an energy spectrum and identifying the photons of interest. The variation in amplification makes this non-trivial. To solve the problem a calibration measurement of the individual anodes would have to be made. As a suggestion a laser and a stepping motor could be used. If the aim is to detect the two γ -rays from a positronium annihilation another solution could be to make a coincidence measurement with detectors on both sides of the reaction.

In experiments to increase our knowledge about particles it is sometimes worse to draw false conclusions than to be unable to draw any conclusions at all. To use this new types of detectors, improvements in the identification of particles has to be made. Our methods are still not reliable enough, so further research is necessary.

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