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Investigation of the Characteristics of ^{252}Cf-detectors

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Master of Science Thesis

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Abstract

A Cf detector is an ionization chamber containing the radioactive element ^{252}Cf. ^{252}Cf decays through alpha decay and spontaneous fission. Each fission produces both neutrons and photons.

In the first chapter the characteristic behaviors of two Cf detectors have been investigated by performing pilot measurements. The detector with the stronger source gives an unstable signal with a low signal/noise ratio. Therefore this detector has not been further investigated.

The ionization chamber reacts on both fission products and alpha decay. An energy experiment showed that there were large difficulties to separate those decays.

A plastic scintillator, which reacts on both photons and neutrons, was used for neutron detection. Energy spectrums were performed and the result showed that it is difficult to set an energy threshold to separate the neutrons and the photons.

The discrimination will rather be achieved by time of flight methods which is discussed under the second chapter in this thesis; Experimental results.

To investigate whether it is possible to detect any delayed components from the spontaneous fission of ^{252}Cf an other experiment was done. The result showed that delayed components existed. Either they are delayed neutrons from exited fission products. Or so it is some delay related to the charge collection in the Cf detector.

Correlation measurements showed that few events are coincident. Only 50% of the signals from the plastic scintillator are correlated with the Cf source.

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Introduction

Measurements and overview of reactivity are of high importance for a number of applications, such as core loading and reactivity measurements. An important tool for these types of measurements can be the use of a ^{252}Cf detector. Two such detectors, of ionization gas type, have been transferred from JNC, Japan.

Several experiments with a ^{252}Cf source and a neutron detector have already been made but a combined source and detector has not been investigated properly. The advantage of having a combined source and detector is that the source is placed in the detector gas. This means that almost every fission event will be detected and a time reference for the neutron emission can be obtained from the ionization chamber without actually consuming any neutrons.

The main aim of this thesis is to perform pilot measurements of the detectors to determine their characteristic behavior which are done in the first chapter.

In the second chapter the detector with lower activity is used in experiments. The first experiment discuss whether it is possible to detect delayed components from the spontaneous fission of ^{252}Cf. Secondly time of flight measurements is performed to investigate the time spectrum of both neutrons and photons. Finally is correlations experiments performed to measure how large fraction of the signals from the Cf detector that are correlated to signals from a neutron detector.

1. The ^{252}Cf detector

1.1 Background

Californium was discovered 1949 in the University of California, Berklay, by Thompson, Ghiorso and Seaborg. They manufactured it by bombarding Curium with helium. Californium has mass number A = 251 and atomic number 98. ^{252}Cf is a radioactive isotope of Cf with a half-life of 2,645 years. The branching ratio of the decay favors alpha decay with 96,91 %. The remaining 3,09 % decays through spontaneous fission which is binary 99,63 % of the times. Figure 1.1 shows the distribution of the fission products [1]. The full line is from experimental results and the dotted line is calculated from the A_p' model, see [1].

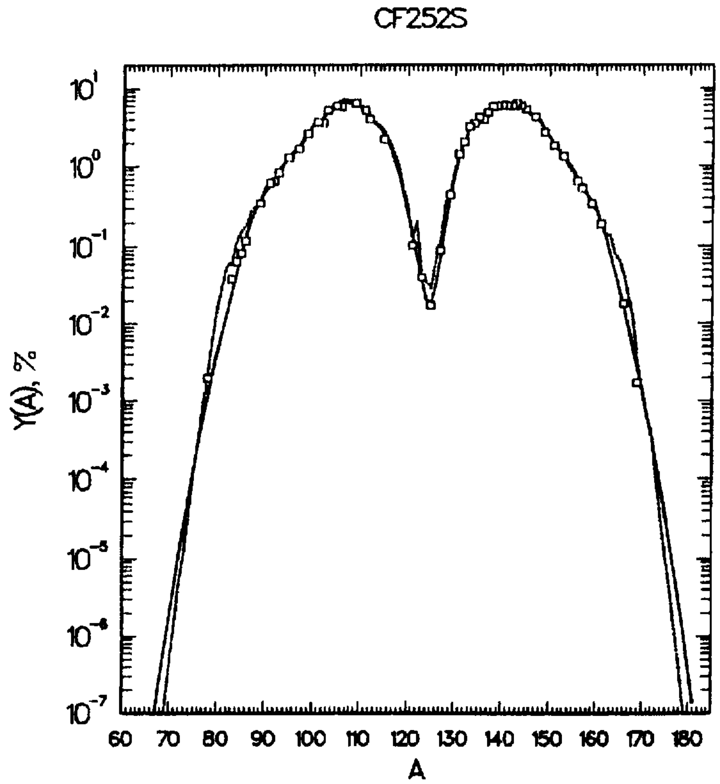

Figure 1.1: The distribution of the products from spontaneous fission of ^{252}Cf in percent. The full line shows data from experimental results and the dotted line is theoretical calculated numbers.

According to experiments the neutron spectrum of ^{252}Cf is similar to that of ^{235}U. Most of the neutrons have energy somewhere between 200 keV and 8 MeV [2].

Each fission yields an average of 10 photons having a total energy of around 8 MeV [3].

The spontaneous fission of ^{252}Cf shows similarity to the spontaneous fission of Uranium and the half life for spontaneous fission makes it practical to use in experiments.

1.2 General information

Most of the information below is from the product information [4] that followed the detectors. The Cf detector consists of an ionization chamber containing a ^{252}Cf neutron source. The detector yields a signal when it detects the fission products from the spontaneous fission of ^{252}Cf. There are two detectors with different source strength. The detectors are supplied with 1000 V and the detector signal is superimposed on this voltage on the same connector. A picture of the detector with lower activity is shown in figure 1.2. The other detector has a similar appearance. The detectors have a weight around 1 kg and are of ionization gas type with a pressure of 1 atm.

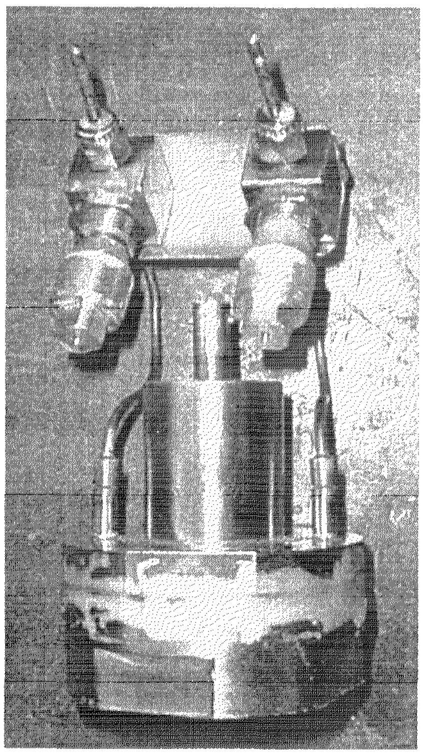

Figure 1.2: The ^{252}Cf detector with low activity.

The detector with lower activity contains Ar – CH_4 as ionization gas. The original intensity of its source was 3.7 MBq (July 1994). The experiments which are described in this work were done in February to June 2004. Using the half life of ^{252}Cf the intensity in April was about 0.3 MBq. Rough measurements which confirm this numbers have been done.

The detector with higher activity, 33,73 MBq (February 1996), contains Ar – CO_2 as ionization gas. Because of a poor output signal from this detector, see section 1.3, it is hard to receive a reliable signal. In the text subsequent of section 1.3 only the Cf detector containing the weaker source will be considered.

Because of the activity, it is advisable to keep the distance to the detectors while working. Direct or close contact with them should be kept to a minimum and dosimeters should be worn.

Several measurements which involve ^{252}Cf have been performed previously. There are one main difference between this experiment and those. In our case the Californium source is placed in the gas detector. Therefore is not easy to test the ion chamber itself because there is always a source located close to it. One part of this work is to establish the characteristic behavior of the ion chamber.

1.3 The signal

To examine the shape of the signals from the Cf detectors they were connected to an oscilloscope via the timing output of a preamplifier, ORTEC 142AH. Figure 1.2a shows the signal from the weak Cf-detector. There is a lot of noise in relation to the signal and thus it was amplified about 500 times with a fast filter amplifier, ORTEC 579. The amplifier was connected directly after the preamplifier and both modules are used in all the following experiments. The signal now obtains the shape shown in figure 1.2b, which is decent to work with.

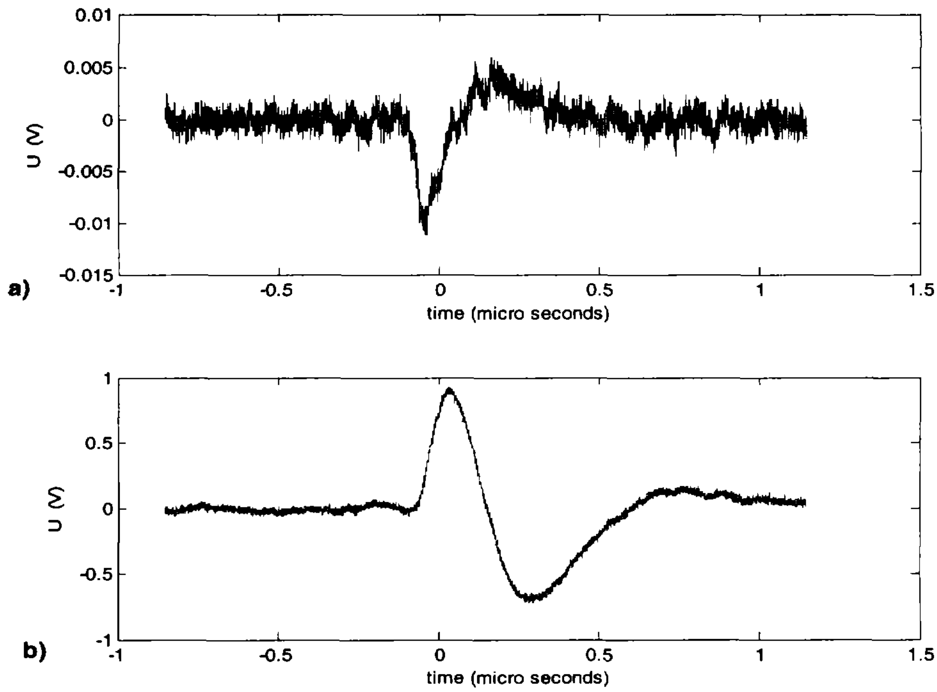

Figure 1.2: **a)** The signal from the detector with lower activity via preamplifier.
b) The signal from the detector with lower activity via preamplifier and further amplified with an amplifier.

The strong Cf detector also gives a signal but with more noise. Figure 1.3 shows the signal after passing through the preamplifier. No stable signal was found and the signal/noise ratio is only about 2 to 1 which makes it hard to work with. After trying to get a better signal without success, it was decided to do measurements only with the weak detector in the continuation of this thesis.

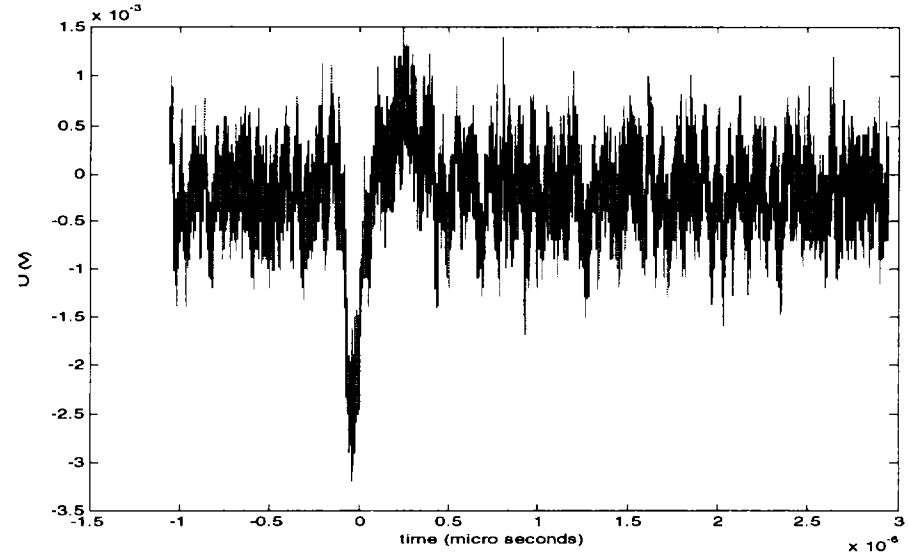

Figure 1.3: The signal from the detector with higher activity via preamplifier.

1.4 High voltage

The Cf detector needs high voltage and the product information recommends 1000 V. An experiment was performed to examine how the Cf detector characteristics depend on the applied voltage. Figure 1.4 below shows schematically how the experiment was arranged.

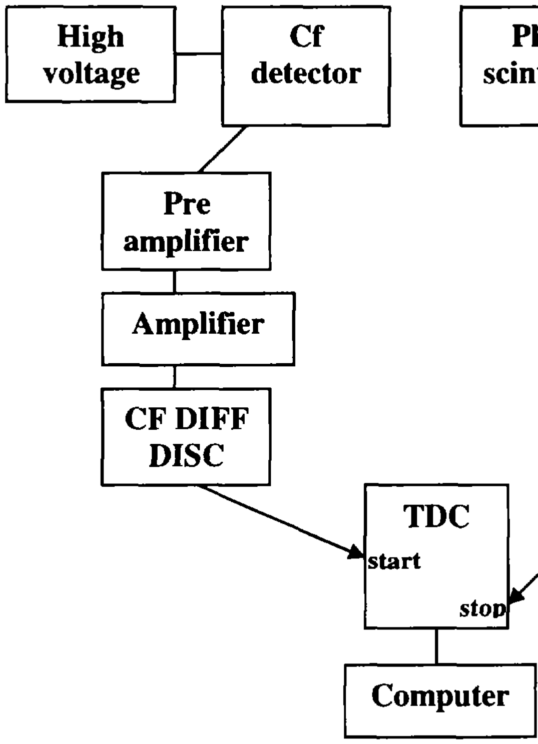

Figure 1.4: Experiment setup for High voltage experiment

The Cf-detector was connected to a high voltage generator and then placed close to the plastic scintillator used as a neutron detector. Moderator plates were placed around the detectors as a reflector to further increase the neutron flux in the detector. The signal from the Cf-detector was amplified and then connected to a CF DIFF DISC (constant fraction differential discriminator). The CF DIFF DISC has a lower level threshold and an upper level threshold and responds only to input signals which fall between these. If this criterion is satisfied, the CF DIFF DISC responds by issuing a standard time signal independent of pulse amplitude. In this experiment the lower level was adjusted to block small pulses. In that way most of the noise was discriminated once the signal was used as start input for the TDC (Time-to-digital converter).

The plastic scintillator was connected to the Time Pickoff control which sets a discrimination level and yields a fast negative timing output. Because some delay in the setup as well as in the Cf detector itself the signal from the plastic scintillator arrives earlier to the TDC then the signal from the Cf detector. To correct this problem the signal from the plastic scintillator was delayed with the Delay amplifier.

The TDC starts a clock when a signal comes from the Cf detector and stops the clock when a signal from the plastic scintillator arrives. A PC was used for data aquisition. One series of measurements with various high voltage supplies was made. The results were normalized wherefore they can be compared in the same coordinate system (see figure 1.5).

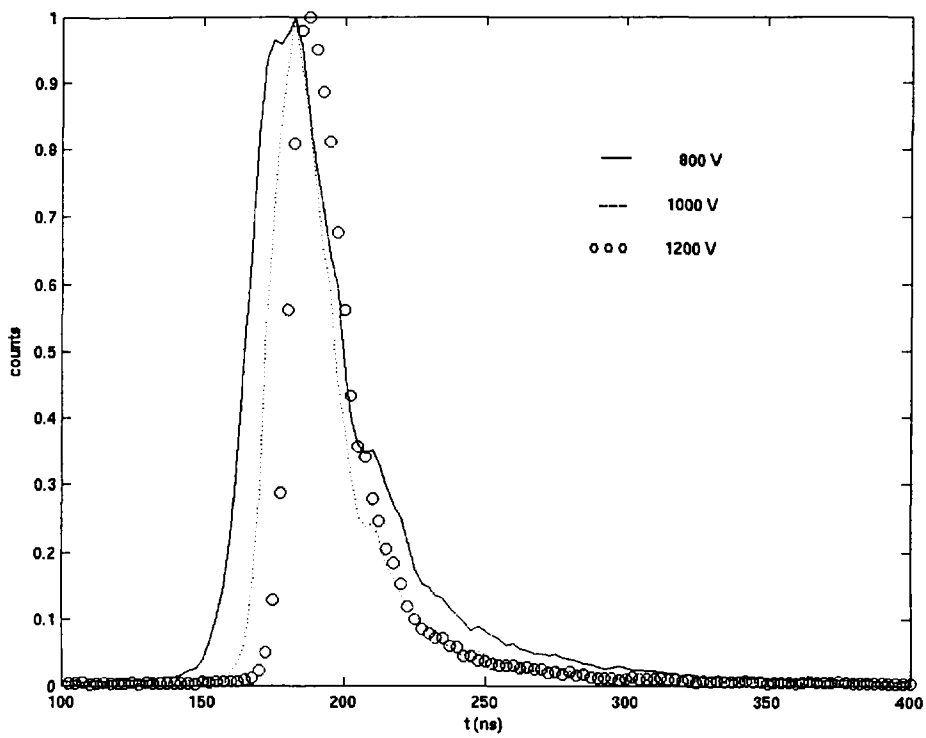

Figure 1.5: The figure shows three measurements with various voltages applied to the ^{252}Cf detector. The three graphs are normalized wherefore the measurements can be compared in the same coordinate system.

The Cf detector is an ionization chamber and most probable the width of the peaks reflect the uncertainty in time inherent in the ion chamber. A higher voltage in the detector will decrease the collection time of deposited ions. This may also explain why the peak shifts to the right direction with higher voltages. When the voltage increases the charged particles move faster and the signal starts the clock on the TDC earlier.

The FWHM (Full with half maximum) of the 1000 V measurement is 25 ns, which is a measure of the Cf-detectors inherent time resolution. This means that in the future measurements (where a high voltage supply of 1000 V always is used) this is the best time resolution that can be expected.

1.5 Threshold

These measurements were done to study the effect of different energy thresholds. The Cf detector gives a pulse when a fission product or alpha particle ionizes the gas. Due to its higher energy the fission product of ^{252}Cf gives a pulse with higher amplitude than a particle from its alpha decay. The maximum pulse amplitude from alpha particles is less then the minimum pulse amplitude from fission products [5]. By setting an energy threshold it should thus be possible to block the pulses originating from alpha particles.

The experimental arrangement is the same as in figure 1.4 but now a plate of lead is placed between the detectors to shield from gamma radiation.

The discrimination level on the CF DIFF DISC was varied. Figure 1.6 shows the normalized results. In all measurements there was no upper discrimination level, the lower discrimination level was successively raised from a) to e). In a) the threshold is very low and a lot of noise is allowed to pass. In e) is the threshold high and the count rate is significantly lowered. The curves for higher threshold have comparatively high statistical variations due to the low count rate.

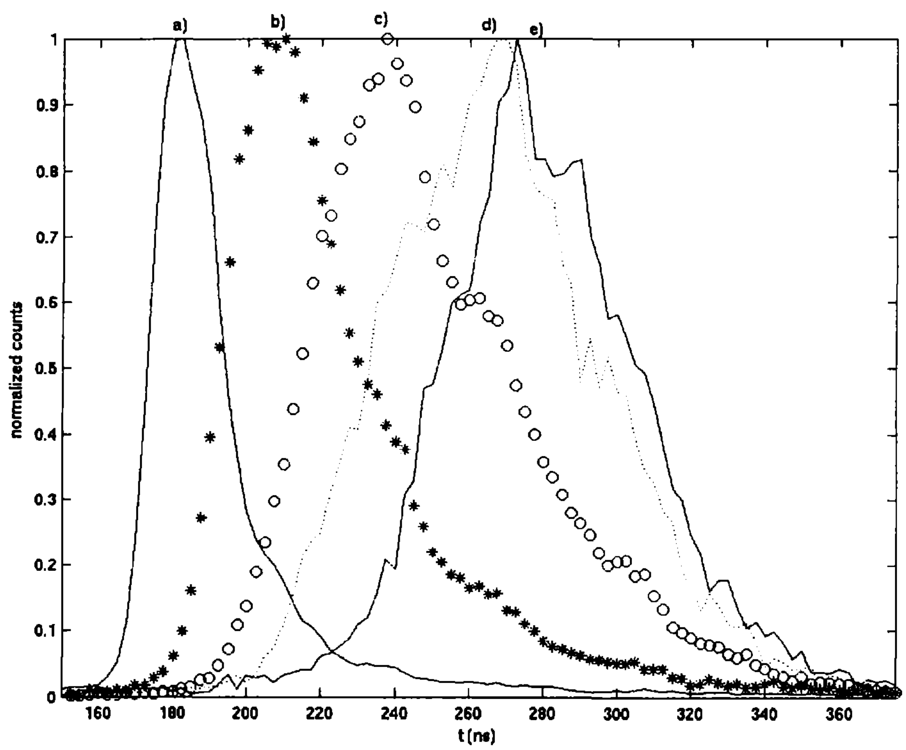

Figure 1.6: The graphs are the result of a measurement series with various energy thresholds. The lower discrimination level is rising from a) to e) but there is on upper level.

Due to the discussion in the beginning of this chapter should the first graph in the picture, a), originate from both alpha decay and spontaneous fission. Somewhere in b) to e) should the graphs just originate from fission products. There is however nothing in the result that confirm this. The only thing figure 1.6 shows is a shifting in time which is an effect of the collection system.

Measurement a) was now repeated without lead. The normalized result is presented beside the measurement with lead in figure 1.7.

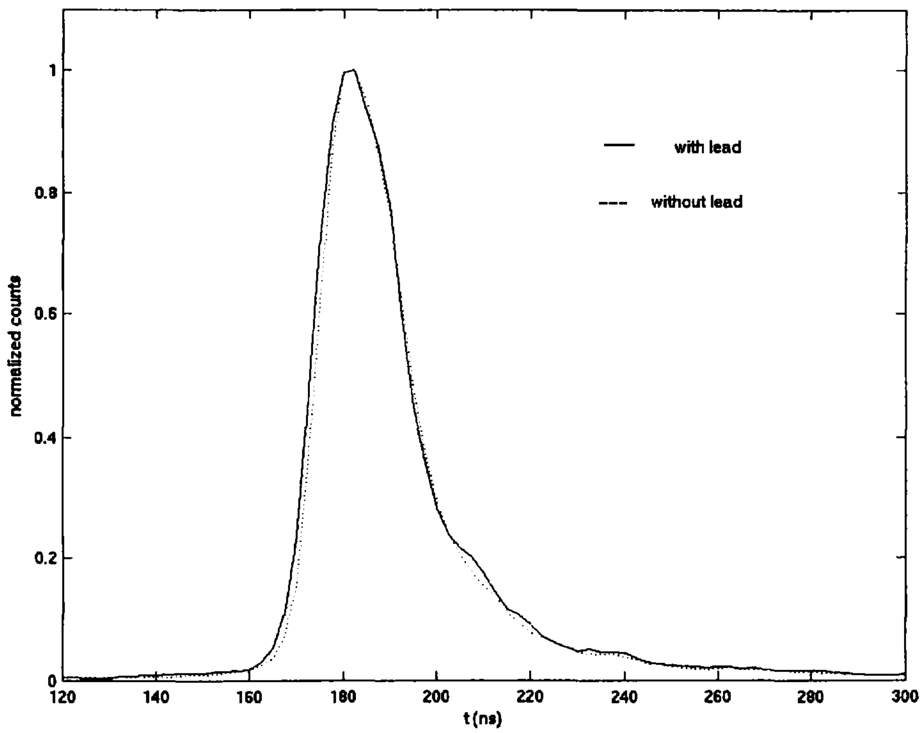

Figure 1.7: Comparison of measurements.

The dotted graph in figure 1.7 shows events from the measurement using no lead. These events are from neutrons and gamma radiation, from spontaneous fission and alpha decay respectively. The expectation was that the measurement using lead would discriminate the gamma radiation and thus give a different graph. As can be seen in the figure there is no difference.

The conclusion is that close to the source the neutrons and gamma radiation have the same distribution over time.

1.6 Energy spectrum

Previous chapter discussed the discrimination of pulses originating from alpha decay. In part 1.6.1 this question is once again addressed through the performance of an energy measurement.

To further investigate if it is possible to separate the signals that arise from neutrons from those that arise from gamma radiation two measurements were made (part 1.6.2 and 1.6.3). At first a plastic scintillator was used to obtain an energy spectrum for the neutrons, and then a BGO detector which is a gamma detector was used to receive a spectrum for the gamma radiation.

1.6.1 Energy spectrum from the Cf detector

As in the previous experiments the signal from the Cf detector was connected to the preamplifier and further to the amplifier. The amplified signal was connected to the ADC IN on an Adcam MCB used for this energy measurement. The result is presented in figure 1.8.

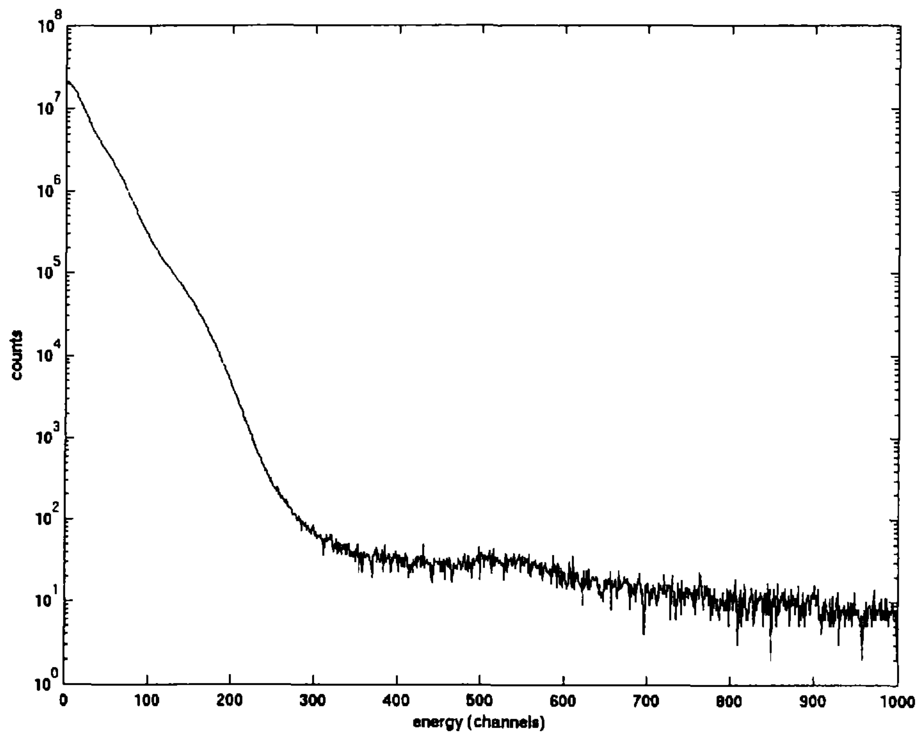

Figure 1.8: Energy spectrum from the Cf detector.

The energy spectrum is a continuous curve instead of, as in an ideal case in an ideal detector, two separate peaks for spontaneous fission and alpha induced events respectively. The result does not show any large possibilities to discriminate signals originating from alpha particles versus fission products.

1.6.2 Energy spectrum of the neutrons

The plastic scintillator was placed near the Cf detector and its signal connected to the ADC IN on the Adcam MCB. The signal from the Cf detector was connected to the GATE input of the MCB. Thus the ADC only collected events in the plastic scintillator correlated with a signal from the Cf detector. The result is presented in figure 1.9.

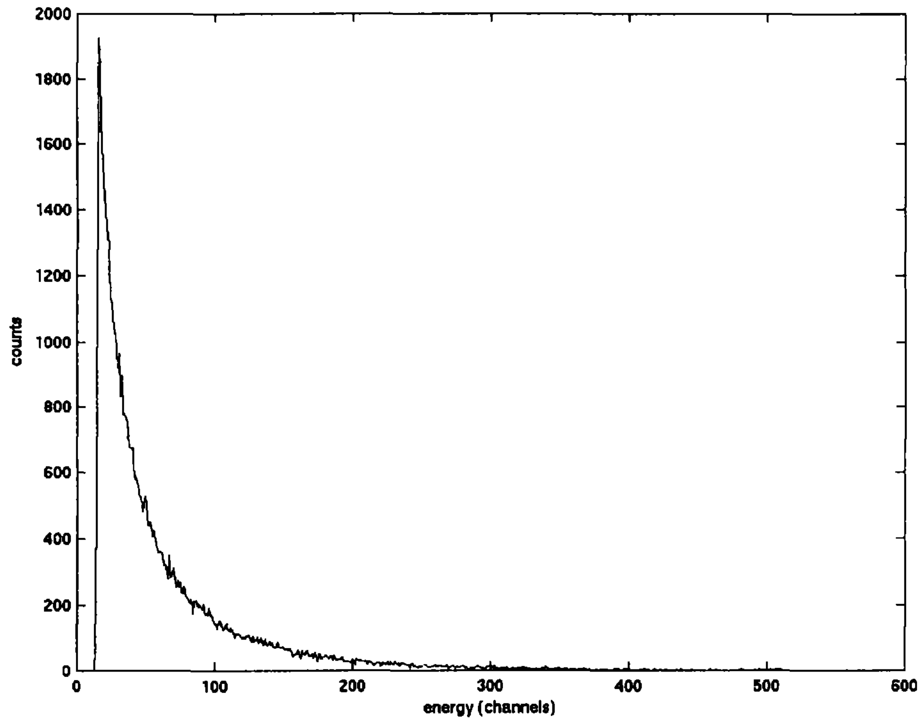

Figure 1.9: Neutron energy spectrum.

1.6.3 Energy spectrum of the gamma radiation

The setup for the BGO detector was arranged in the same way as the plastic scintillator. Figure 1.10 shows the result.

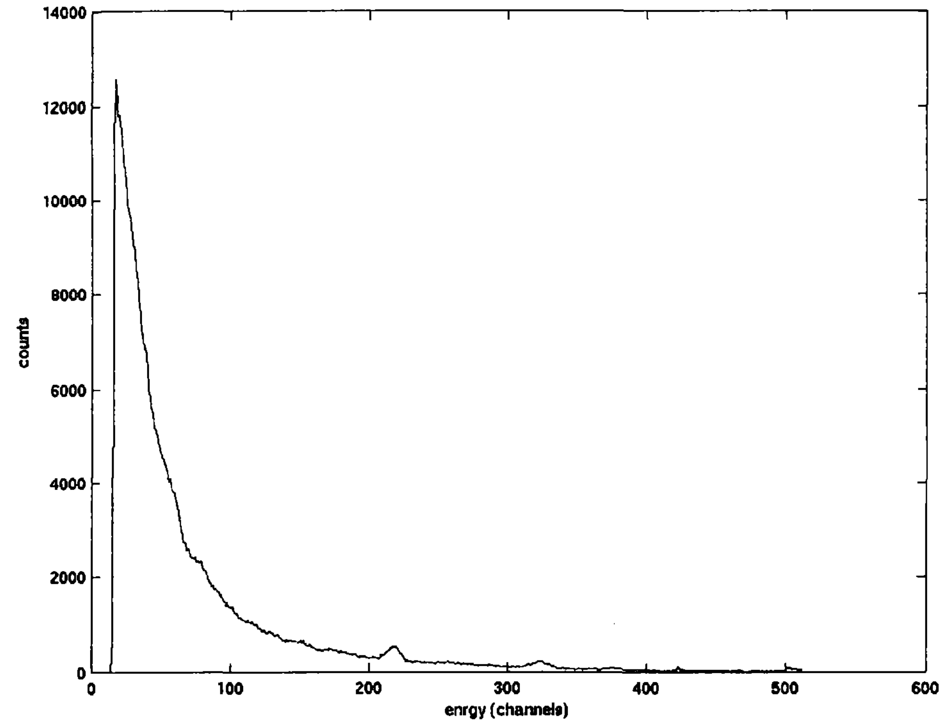

Figure 1.10: Energy spectrum from gamma radiation.

Just as in the figure for the neutron spectra there is a continuous curve over the energy interval. This means that it is difficult to set an energy threshold to separate the neutron and the gamma radiation.

2. Experimental results

2.1 Delayed components

This experiment was done to investigate whether it is possible to detect any delayed components from the spontaneous fission of ^{252}Cf. The arrangement of the experiment can be seen in figure 2.1. There where also reflectors placed around the detectors.

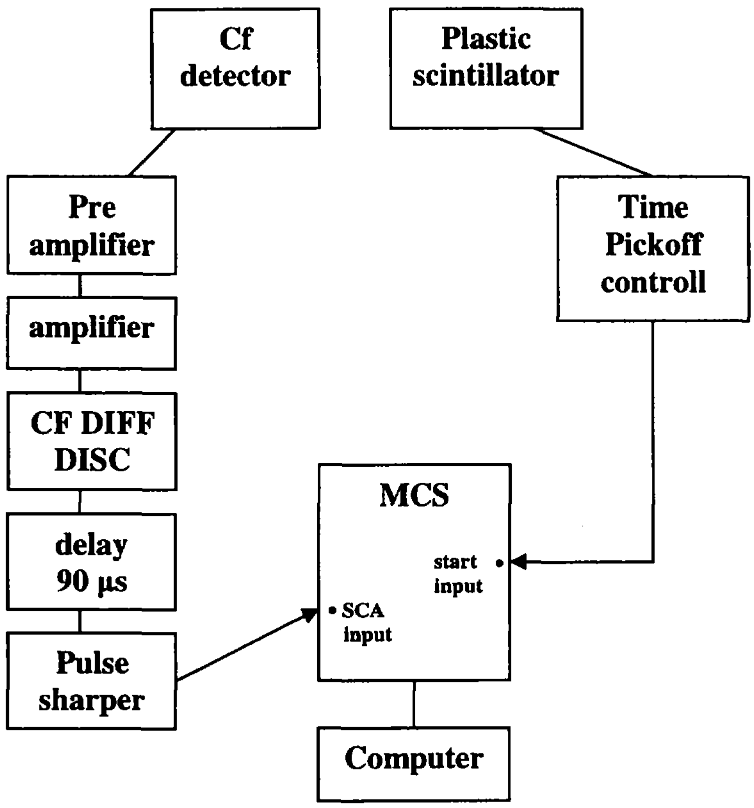

Figure 2.1: Experimental arrangement.

To avoid start signals from the Cf detector, without any correlated signals from the plastic scintillator, the input order was changed. The signal from the plastic scintillator was used as start and the other, from the Cf detector, as stop. The signal from the Cf detector was delayed about 90 micro seconds to receive time to discover delayed components. After a start signal the MCS (mulitchannel scaling) sweeps 120 μs. During that time it collects signals from the Cf detector.

It was possible to visually follow the development on a computer screen until enough data was collected. Because of the reversed order, with the plastic scintillator as start it is easier to study the mirror image with correct time axis, as shown in figure 2.2.

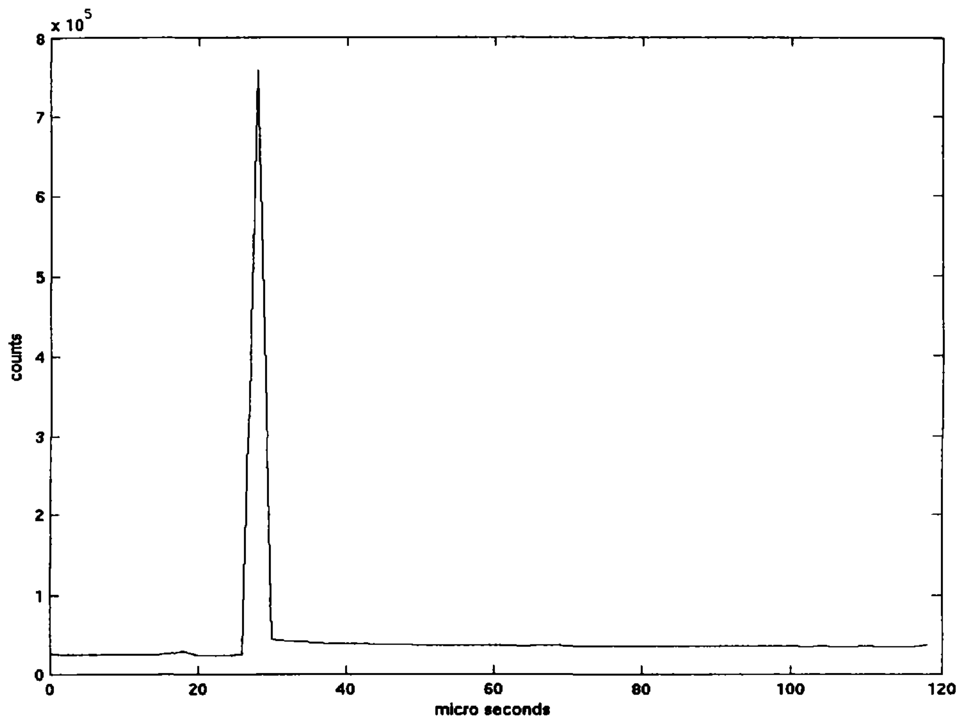

Figure 2.2: The mirrored image with correct time axis. The peak derives from a combination of gamma rays and neutrons. The level to the left of the peak is from background noise and uncorrelated events. Note that the scale on the x-axis is relative and not in absolute values.

The level before the peak derives from uncorrelated events and background noise. After the peak there is a small slope on the graph. The slope could arise from the activity from either radioactive fission products or neutron induced elements. In that case it is possible to calculate the half-life of the element which causes the neutrons.

$N = N_0 \cdot e^{-\lambda t}$

λ = decay constant,

N = number of nuclei

N_0 = number of nuclei at time t =0

is the radioactive decay law. The half life is: $t_{1/2} = \frac{\ln 2}{\lambda}$

If a line is fitted to the logarithmic curve between 64 and 114 μs according to the least square method it gives figure 2.3.

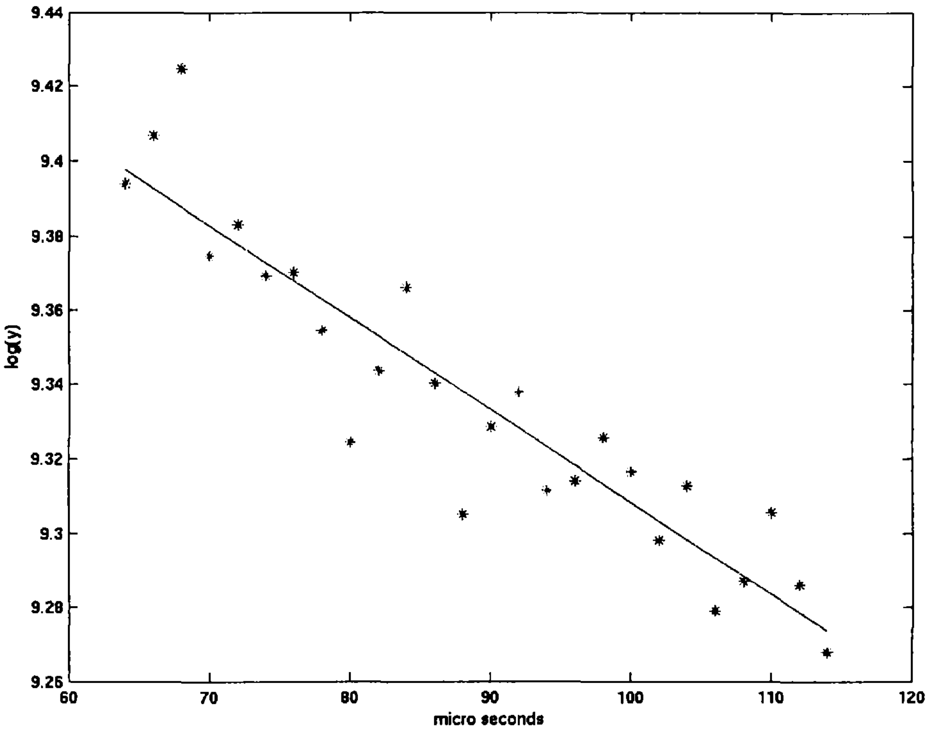

Figure 2.3: The stars are measured points and the straight line is its linearly adaptation according to the least square method.

The Matlab commands polyfit and polyval was used to compute the graph. Those commands also give an estimate of the uncertainty. In this case the slope on the graph, in the actual interval, which correspond to minus the decay constant λ is -0,0025 ±0,0007. This gives

$$t_{1/2} = \frac{\ln 2}{\lambda} = \frac{\ln 2}{0,0025 \pm 0,0007} \quad \rightarrow \quad 216\mu s \le t_{1/2} \le 385\ \mu s$$

No corresponding half-life was found in the data base making neutron induced activity less probable. There are now two possibilities remaining. Either the delayed components are delayed neutrons from exited fission products. Or so does the slope showing that it is some delay related to the charge collection in the Cf detector. Whichever possibility that is more probable is not possible to conclude.

2.2 Time of flight

To further investigate the time spectrum of both neutrons and gamma rays a series time of flight measurements was done. The experimental arrangement is described in figure 2.4 below. As before the setup after the Cf detector gives some delay, wherefore the signal from the plastic scintillator arrives to the TDC first. To minimize the dead time the signal from the plastic scintillator is plugged to the start input in the TDC.

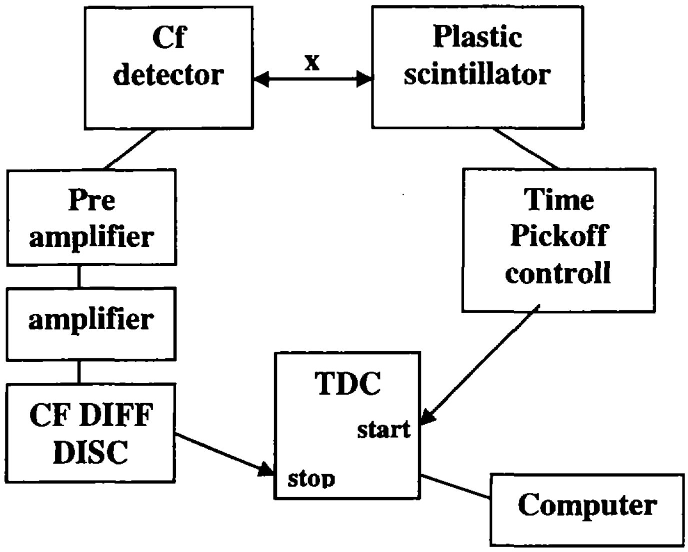

Figure 2.4: Set up for Time of flight measurements.

A set of measurements with various distance x between the detectors were performed. The results for **x** = 0, 40, 100 and 150 cm are illustrated in figure 2.5. Because of the reversed order, with the plastic scintillator as start it is easier to study the mirror image with correct time axis.

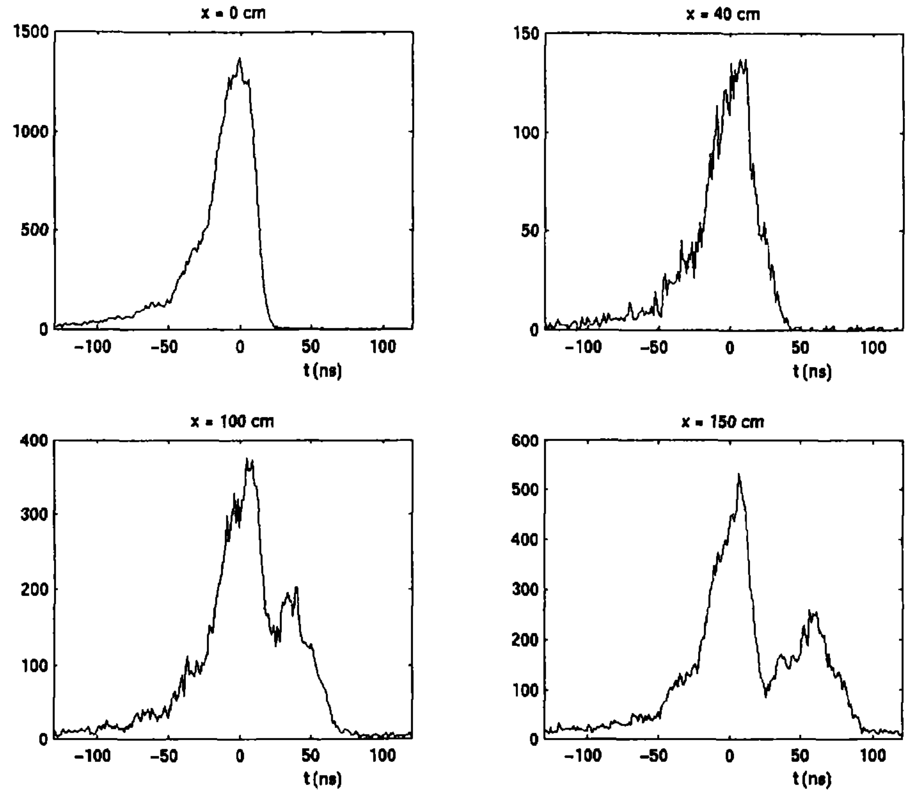

Figure 2.5: The graphs show the results from Time of flights measurements with various distances **x**.

The first events on the left side of the main peak show noise and uncorrelated signals. As the distance increase, the main peak gets broader and split up. In the fourth figure with **x** = 150 cm two peaks are clearly seen. The largest peak is at an almost constant position but a smaller peak which at first was in superposition with the larger one is shifting in time.

The conclusion is that the main peak arises from gamma radiation, which moves with the speed of light and covers the full path of 150 cm in 5 ns. The peak that shifts must be originating from something that moves much slower, neutrons.

To confirm the hypothesis that the two peaks arise from different particles the experiment was repeated. The distance was 150 cm but now a 3 mm plate of lead was placed between the detectors to shield from gamma radiation.

In figure 2.6 the result are shown beside the one that were done previously without lead. The figures show that the relation between the peak for gamma and neutrons has changed when lead is used. The lead has shielded a part of the gamma radiation.

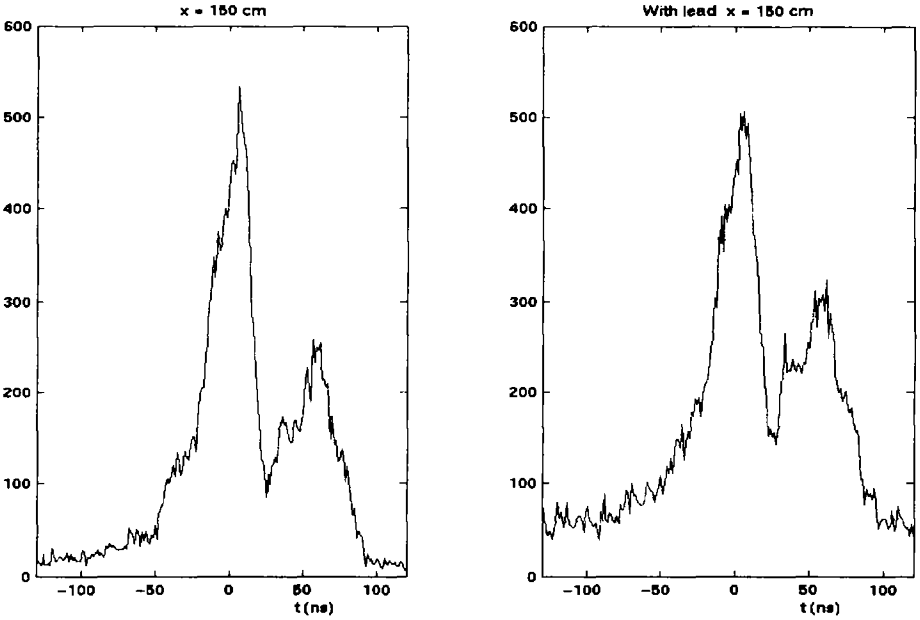

Figure 2.6: Time of flight measurements with the distance 150 cm. In the right figure there are lead between the source and the plastic scintillator.

It is possible to make a rough calculation of the mean energy for the neutrons. To determine the peak position we use the cross values when the peak amplitude passes 50 % of the total peak amplitude. Assuming that the part of the peak in figure 2.5 with **x** = 0 cm that correspond to the neutrons have the same position as the total peak, the neutron peak for **x** = 0 cm is positioned at $\frac{-15,5+15,5}{2}$. The mean neutron time of flight then is 0 ns. When the neutrons have traveled 150 cm longer (figure 3.5, **x** =150 cm) the cross value occurs at $\frac{36,5+79,5}{2}$ = 58 ns. The mean neutron have then traveled 150 cm in 58 ns. Because the speed of the neutron is less then 10% of the speed of light there is no need for relativistic calculations. The mean energy **E** is then:

$$E = \frac{mv^2}{2} = \frac{1{,}008665 \cdot 1{,}660566 \cdot 10^{-27}}{2} \cdot \frac{1{,}50^2}{(58^{-9})^2} = 5{,}6014 \cdot 10^{-13}\,\mathrm{J} = 3{,}496\,\mathrm{MeV}$$

The general formula for the max error is

$$|\Delta y| \leq \left|\frac{\partial f}{\partial x_1}\right| |\Delta x_1| + \ldots\ldots + \left|\frac{\partial f}{\partial x_n}\right| |\Delta x_n|. \qquad [4]$$

In this particular case the formula is

$$|\Delta\mathbf{E}| \leq \frac{m}{2}\left|\frac{\partial\left(\mathbf{x}^2/\mathbf{t}^2\right)}{\partial\,\mathbf{x}}\right||\Delta\mathbf{x}| + \ldots\ldots + \left|\frac{\partial\left(\mathbf{x}^2/\mathbf{t}^2\right)}{\partial\,\mathbf{t}}\right||\Delta\mathbf{t}| =$$

$$= m\left|\frac{\mathbf{x}}{\mathbf{t}^2}\right||\Delta\mathbf{x}| + \ldots\ldots + m\left|-\frac{\mathbf{x}^2}{\mathbf{t}^3}\right||\Delta\mathbf{t}|$$

If $\mathbf{x} = 1{,}50$ m, $\Delta\mathbf{x} = 0{,}01$ m, $\mathbf{t} = 58$ ns, $\Delta\mathbf{t} = \frac{(15{,}5+15{,}5)+(79{,}5-36{,}5)}{4} = 18{,}5$ ns

then $\Delta\mathbf{E} \leq 2{,}277$ MeV

Finally $\mathbf{E} = 3{,}5 \pm 2{,}3$ MeV

The uncertainty is largely dependent of the poor time resolution for the Cf detector (Chapter 1.4). There where no expectations for mono energetic neutrons, the uncertainty gives information about the energy distribution of the neutrons.

2.3 Correlations

The pulses from an ideal Cf-detector are induced by fission products only. If a plastic scintillator is placed adjacent to such a Cf detector it will only yield signals correlated with those from the Cf detector. In our case however we do not really know how often the Cf detector reacts on alpha particles. It is then of high interest to measure how large fraction of the signals from the Cf detector that are correlated to signals from a plastic scintillator.

The arrangement for a time resolved activity measurement is shown in figure 2.7 below. The computer program Counter/timer874.vi was used to treat the information from the Quad counter/timer.

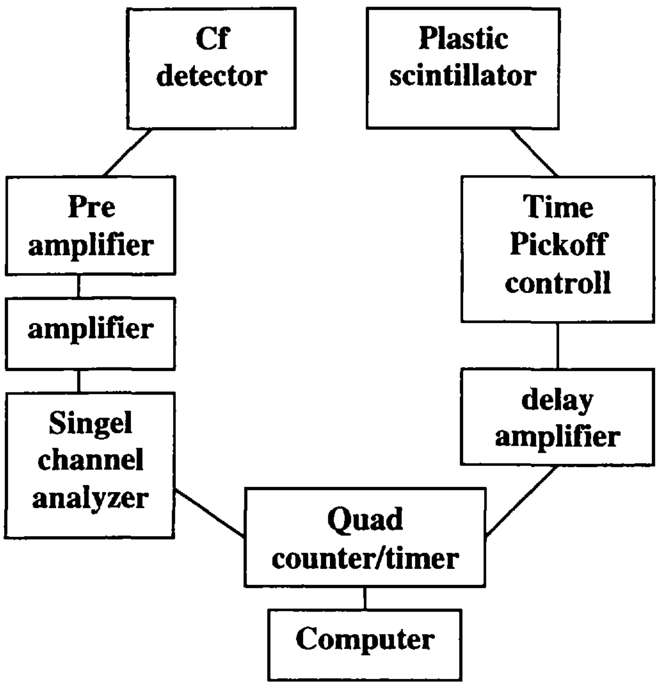

Figure 2.7: Setup for correlation measurements.

In the first measurement the computer program counted all pulses from the Cf-detector and the neutron-detector for every 0,1 second (Figure 2.8).

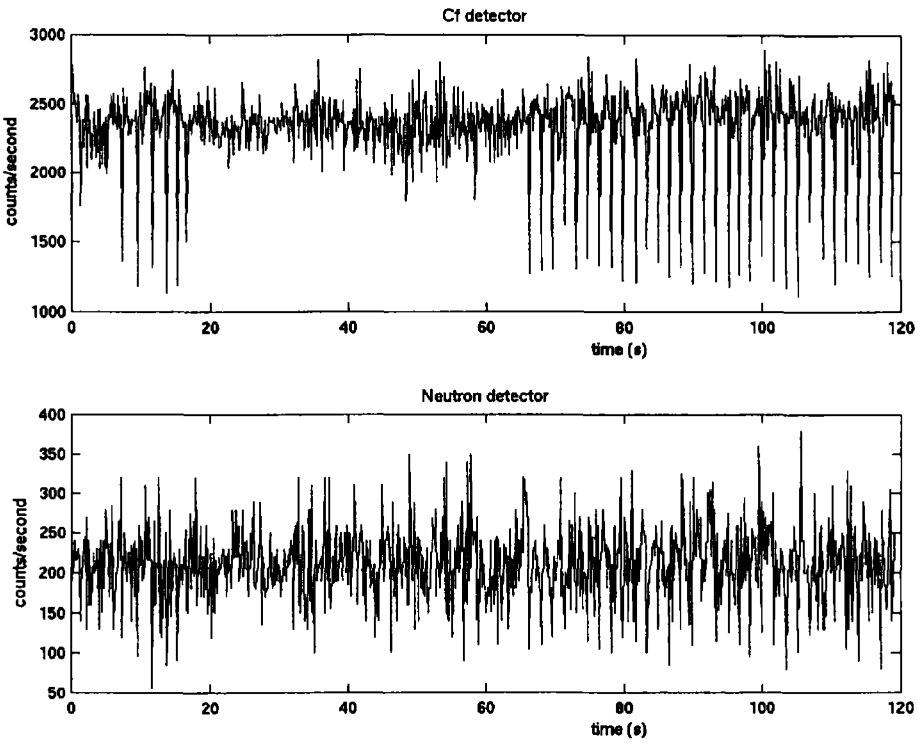

Figure 2.8: Time resolved activity measurement. The computer program counted the signals every 0,1 s.

Obviously the computer system had problems with the short collection time, 0,1 second, which is the explanation of the non-physical deep peaks. In the continuation of this experiment the collection was done with larger time bins. When another measurement with collection time 0,2 s was done, the result became much better (figure 2.9).

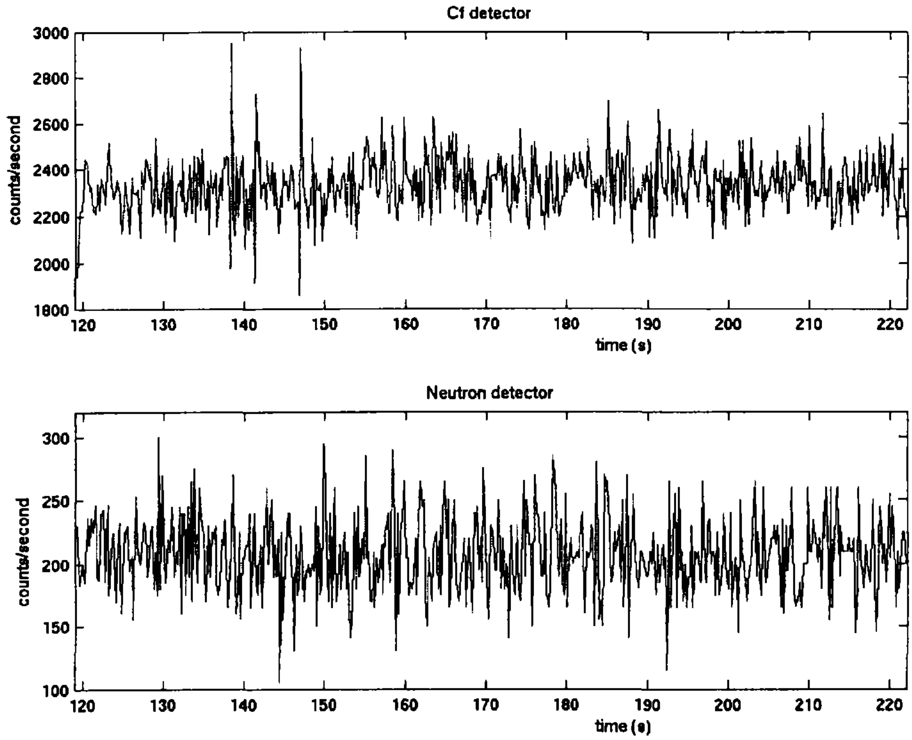

Figure 2.9: Time resolved activity measurement. The computer program collected the signals every 0,2 s.

The figure shows that the count rate for the Cf detector is about 10 times higher then the count rate from the plastic scintillator. A much higher count rate for the Cf detector was expected. There is a high possibility that neutrons will miss the detector because of the small solid angle. Also the Cf detector reacts on alpha decays which do not produce any neutrons.

The experiment was now repeated with some changes. The discrimination level for the Cf detector was lowered and some lead was placed between the detectors to shield from some of the gamma particles. The signals from the detectors were also connected to a coincidence module. The coincidence module gives a signal when the signals from the two detectors arrive at the same time. The output was connected to the Quad counter/timer which then also counts how many of the signals from the two detectors that are correlated.

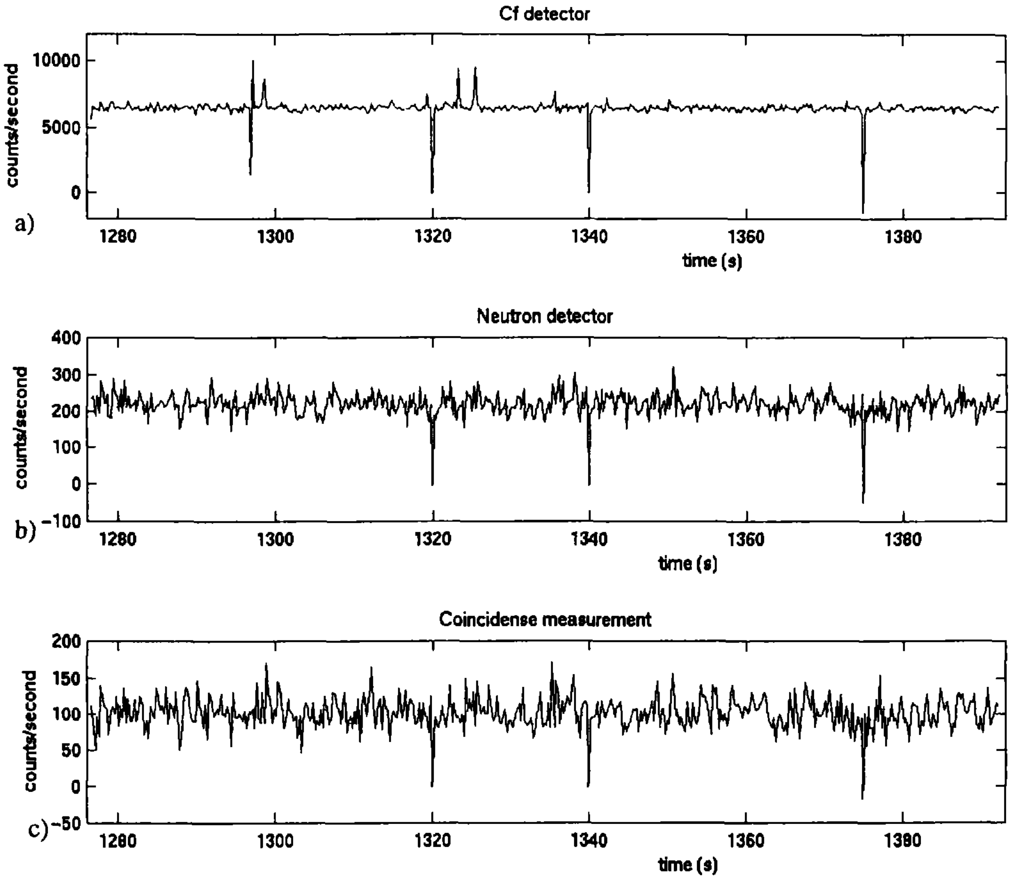

Figure 2.10: The computer program collected the correlated signals every 0,2 s. **a)** Signals from the Cf detector. **b)** Signals from the plastic scintillator. **c)** Coincidental events.

The result (figure 2.10) shows how many of the signals from the two detectors that are coincidental. Few events are correlated, only 50% of the signals from the plastic scintillator are correlated with the Cf source.

Conclusion

The ^{252}Cf detectors provide promising tools for time resolved neutron measurements, but great care has to be taken for the intrinsic properties of the detectors both with regard to the sensitivity to alpha decays and the poor time resolution of the detector.

Acknowledgements

First and most importantly I would like to thank my supervisor Anders Nordlund for his guidance through the diploma work.

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Finally I would like to thank everyone at the department for making my stay here pleasant.

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