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Measurements of low energy nuclear recoil tracks and their implications for directional dark matter detectors

Christina Hagemann

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Measurements of low energy nuclear recoil tracks and their implications for directional dark matter detectors

by

Christina Hägemann

Vordiplom, Rheinische Friedrich-Wilhelms-University Bonn, 2001
M.S., University of New Mexico, 2005

DISSERTATION

Submitted in Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy
Physics

The University of New Mexico

Albuquerque, New Mexico

December, 2008
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Acknowledgments

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Abstract

Directional dark matter detection is needed to unambiguously detect a dark matter particle interaction in a detector. This is due to the fact that only a dark matter signature will have its incoming direction vary throughout the day due to the rotation of the earth. This directional signature could only be measured in a gaseous detector as used by the DRIFT detector, currently taking data with one module at the Boulby mine in the UK. Gas has to be used as the detection media to allow for longer tracks that can be resolved in three dimensions and a vector direction, resulting in the possibility of measuring the incoming direction of the WIMP that created the recoil.

The prototype detector presented in this Dissertation is used to fundamentally investigate the properties of the low energy nuclear recoils induced by WIMP interactions in a real directional dark matter detector. Measurements are presented
that have been performed using neutrons to create nuclear recoils in the detector that are in the range of recoil energies expected from WIMP interactions. It has been measured how well the track can be reconstructed in three dimensions using the detector described.

Furthermore, it is expected that the nuclear recoils at these low energies have an asymmetry of charge along the track. This asymmetry, if it is distinctly different at the beginning of the track than the end, can be used to assign a vector direction to the nuclear recoil. If this is possible for WIMP interactions expected, the amount of events needed to positively detect a dark matter signal can be significantly decreased. A fundamental study of this so called Head-tail asymmetry in the charge distribution has been performed with the prototype detector and is presented.
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Chapter 1

The case for dark matter

The idea of dark matter was first introduced by F. Zwicky in 1933 [1]. When studying the movements of galaxies in the Coma cluster, a galaxy cluster consisting of about 10000 galaxies at a distance of approximately 90Mpc, he found a discrepancy between the mass measured from dynamical considerations and the mass determined from the luminosity of the galaxies. He attributed this discrepancy to a mass that did not emit any radiation in the visual bands he observed. This would require a missing mass component to exist in the cluster, that was non-luminous or dark and could therefore not contribute to the luminosity of the galaxies.

This discovery was widely disregarded in Zwicky’s time, since there was no other evidence supporting this theory for “dark matter”. Today, on the other hand, there is overwhelming evidence for the existence of this dark matter. The observational evidence for dark matter will be discussed in this Chapter, as well as what this dark matter could be. How the dark matter, if it exists in the form of a novel, exotic particle, could be directly detected on earth is shown in the last Section.
1.1 Observational confirmations for the existence of dark matter

Since Zwicky’s initial observation, many more, very different observations have been made, confirming the existence of dark matter or in more general terms, that hint at a missing mass that is not understood. A couple of these observations will be discussed in the following Sections.

The observational evidence presented is found from galactic rotation curves, gravitational lensing and the so called “Bullet Cluster”. Indications for the existence of dark matter from Big Bang Nucleosynthesis (BBN) and the cosmic microwave background radiation (CMB), demonstrating a different approach to show a need for the existence of dark matter, will be discussed in some detail as well.

1.1.1 Evidence from galactic rotation curves

In 1959 the first galactic rotation curve was observed [2], which indicated that there was a discrepancy between the observed rotation curve and the expected rotation curve in a galaxy. The first complete study of a galactic rotation curve was performed by V. Rubin in 1970 [3].

A rotation curve is a plot of the orbital velocity $v$ of the stars or the gas in a galaxy with respect to the radial distance $r$ to the galactic center. An example of a galactic rotation curve is shown in Figure 1.1 [4].

For the rotation curve, the velocity of the stars or the gas in the galaxy is measured from the Doppler shift of emission and absorption lines. It can be seen that the measured rotation curve (shown by the points and error bars in Figure 1.1) rises sharply and then flattens out at larger distances from the galactic center.
The expected rotation curve, plotted in Figure 1.1 as “disk”, is calculated from dynamical arguments by only considering the visible matter in the disk of the galaxy. The curve is expected to rise sharply from the center of the galaxy at low radial distances from the center. Then a turnover region is expected to exist where the velocity peaks and then drops again with larger r. The last part of the rotation curve is the so called Keplerian region where v decreases as $\frac{1}{\sqrt{r}}$. This is where the expected rotation curve starts to differ from the measured rotation curve, which does not exhibit this Keplerian behavior. To create the flat curve that is measured the stars must revolve much faster than would be expected if they were in a free Newtonian potential.
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One possible way to resolve this is by noting that the predominant matter component of baryonic matter in a galaxy is not in the stars but comes from the ionized x-ray gas that comprises the interstellar medium. The expected rotation curve, just from this gas, is plotted in Figure 1.1 as “gas” and in combination with the rotation curve of the stars, also does not create the flat curve that has been measured. An explanation for the remaining discrepancy is that there is a substantial amount of matter far from the center of the galaxy that is not emitting any radiation, so called dark matter. When concentrating the dark matter component in a halo around the galaxy and extending it far beyond the range of visible matter, the curve titled “halo” in Figure 1.1 is added to the expected rotation curve. Now the measured rotation curve (points and error bars) matches perfectly well with the expected curve (solid line). Introducing a dark matter component to solve the rotation curve discrepancy has been very well received by many scientists. The reason for this is that it is a solution that requires the least adjustment to the physical laws of the universe.

Other theories have also been introduced to explain this rotation curve problem, one of them being Modified Newtonian Dynamics (MOND) [5, 6, 7]. In brief, this theory proposes a modification of Newton’s second law of motion. The idea is that Newton’s law has not been tested for very small accelerations, as would be the case for stars being far away from each other on the outside regions of the galaxy. When modifying Newton’s law at small accelerations, measured rotation curves can be matched with expected rotation curves by only assuming baryonic matter. This theory is still very controversial and has yet to prove how powerful or useful it really is. Newer experimental evidence for dark matter will be presented in the next Sections, conflicting with the MOND theory.
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1.1.2 Evidence from gravitational lensing

Gravitational lensing is based on the principal that light from a distant source will be bent around a massive object (for example a galaxy cluster), located between the source and an observer. Gravitational lensing is one of the predictions of A. Einstein’s general theory of relativity. The mass from the massive object will bend space-time and therefore the paths followed by a light ray past the object will also be bend. This alters the image of the object and can both magnify and distort the image of the source. How this works is depicted in Figure 1.2.

Figure 1.2: Principle of gravitational lensing.

Maximum “bending” of the light ray occurs closest to the center of the gravitational lens. In the optimal case where the source, the lens and the observer lie in a
Chapter 1. The case for dark matter

straight line, the source will appear as a ring behind the massive object forming the lens, which is also referred to as an Einstein ring. If the alignment is not optimal, the source can be observed as partial arcs around the lens and multiple images of the source might be seen. The number of images seen and the shape of them depends strongly on the relative positions of the source and the lens to the observer and the gravitational potential of the lens.

Gravitational lensing is quantified into three different types of lensing: weak, strong and micro-lensing. Strong lensing is identified most easily out of the three. It describes the situation when the distortions of the images are very large and manifest themselves in Einstein rings, arcs and multiple images. Weak lensing describes a situation in which the distortions of the background sources are much more subtle. To detect weak lensing, large numbers of sources are needed and they are statistically analyzed to reveal a shear perpendicular to the direction to the center of the lens. In micro-lensing, no distortions are seen, but the amount of light received from a background source will vary with time.

An example of a galaxy cluster strongly lensing background galaxies can be seen in Figure 1.3. The lens is the galaxy cluster Abell2218 and the distortions of the background galaxies can be readily seen.

Using gravitational lensing, the total mass as well as the mass distribution of a galaxy cluster that constitutes the lens can be determined. Again, it is found that the mass determined through gravitational lensing does not match the mass determined from the luminous matter and the gas in the cluster. Also, when computing the mass distribution in the galaxy cluster in Figure 1.3 it is found that the distribution of matter underlying the entire cluster is very smooth. It falls off to the edge of the cluster but does not just promptly end with the visible matter.

This effect can be seen in Figure 1.4. On the left, a picture of the galaxy cluster
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Figure 1.3: Example of strong lensing. The foreground cluster, Abell 2218, strongly lenses the background galaxies which can be easily identified in the picture.

CL0024+1654 in the visible is shown. On the right, a plot of the mass distribution of the same cluster as determined by gravitational lensing is shown. Underlying the spikes, which are produced by the individual mass distributions of the galaxies making up the cluster, a smooth, underlying mass distribution can be seen. This is thought to be due to the galactic dark matter halo of the cluster.

Gravitational lensing gives very strong evidence for dark matter. The only question that is still not answered from these discussions is what this missing mass component is made up of. If it is a new, exotic particle or possibly baryonic matter hidden in the galactic halo in some way cannot be proven using this method. Luckily, other methods can be used. The “bullet cluster” observation is an example of an observation that indirectly supports the evidence for the existence of dark matter.
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Figure 1.4: Mass distribution of the galaxy cluster CL0024+1654. A picture of the cluster in the visible is shown on the left and the mass distribution as determined from gravitational lensing is plotted on the right. The smooth distribution underlying the spikes is thought to be due to the dark matter distribution in the halo of the galaxy cluster. The various spikes are due to the individual galaxies comprising the cluster. See for example [8] and is discussed in the following.

1.1.3 Evidence from the bullet cluster observation

The bullet cluster - galaxy cluster 1E0657-558 - is a special case of an astronomical incident that had never been observed before. It is an example of two galaxy clusters that collided, moved through one another and are now separated again. This was observed in 1998 [9] and can be used to give another proof for the existence of dark matter [10]. One reason this is such a rare observation is that the plane of the collision is perpendicular to the line of sight.

A picture of the bullet cluster is shown in Figure 1.5. This picture consists of three separate measurements overlaid in one picture. First, the red “clouds” in the
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Figure 1.5: Combined picture of the x-ray emissions (red), gravitational potential (blue) and the optical picture of cluster 1E 067-558, showing a collision of two galaxy clusters.

picture are measurements of the x-ray emission of the ionized plasma that makes up the interstellar gas. A very nice bow shock can be seen in the gas on the right of the picture. It should be noted here that the major component of the baryonic mass is inside the interstellar gas, shown in red here, for every galaxy. As this gas interacts, it slows down and heats up. The second component shown is the blue “clouds”, which map the mass distribution or the gravitational potential of the galaxy clusters, as determined from gravitational lensing. They are separated from one another and from the x-ray gas. They nicely overlap with the third component of the picture, taken in the visible. The stars in the individual galaxies comprising the two clusters
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overlap very well with the gravitational map.

The novelty of this observation is that the gravitational map of the mass distribution matches up with the visible material in the galaxies. If there was no dark matter, the mass distribution should match up with the major baryonic matter component, which is in the ionized gas. Since the dark matter is collision-less, it would be expected to not interact in the collision of the galaxies, just like the stars and therefore stay in its initial halo throughout the collision.

This means, that this observation confirms the existence of dark matter in the galactic halo. It also seems to rule out MOND, whereas this claim is not accepted across the MOND community and adjustments have been made to the theory to include the bullet cluster observation \cite{11}. This does not rule out other ideas though, for example that the missing matter could still be made up of massive halo objects or small black holes. These objects would also not interact in a collision as described above. This statement can be disproven by looking at cosmological arguments from the CMB and BBN used to evaluate the baryonic mass density of the universe.

1.1.4 Evidence from Cosmology - Cosmic Microwave Background radiation and Big Bang Nucleosynthesis

There is other, maybe more compelling evidence for the existence of dark matter, that comes from the cosmic microwave background (CMB) radiation in combination with Big Bang Nucleosynthesis (BBN). The CMB will be introduced first and BBN and its importance to the results from the CMB discussion will be considered in the second section.
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The CMB anisotropies and their implications

The CMB has been measured through different experiments after being discovered in 1965 by A. Penzias and R.W. Wilson of Bell Labs [12] after being proposed G. Gamow and R. Alpher in 1948, see e.g. [13]. The CMB is a form of electromagnetic radiation with a thermal black body spectrum at a temperature of 2.725K, that fills the entire universe. The CMB radiation, together with cosmological redshifts are seen as the best evidence for the validity of the Big Bang theory. By measuring the CMB radiation and its anisotropies various statements about cosmological variables can be made.

In Big Bang (BB) theory, the CMB radiation is a relic radiation from early times of the BB. The early universe was made up of a hot plasma of photons, electrons and baryons, with the photons constantly interacting with the plasma through Thompson scattering. Until about 300,000 years after the Big Bang, the universe had expanded and adiabatic cooling caused the plasma to cool to the point where the photon energy dropped below the binding energy of H and allowed protons and electrons to form hydrogen atoms. This allowed the photons to decouple from the matter and freely travel through the universe. This radiation has successively cooled and is observed today as the CMB radiation at a temperature of 2.725K. After decoupling of the photons, the baryonic matter was able to cluster by gravitational attraction and create larger scale structures. It can be shown that in order for these structures to form, there had to be primordial perturbations in the matter and energy distributions. These fluctuations of the matter density will leave imprints in the CMB radiation as temperature anisotropies. These anisotropies of the CMB radiation have been detected at the $10^{-6}$ level over angular scales of about $7^\circ$ by various experiments mapping the radiation across the sky [14, 15]. Most recently the WMAP experiment [16] measured an all sky map of the temperature anisotropies. This is shown in Figure 1.6.
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Figure 1.6: Anisotropies of the CMB radiation as measured by the WMAP satellite. This is the 5 year results published by the WMAP collaboration in 2008

The measured anisotropies manifest themselves in the angular power spectrum of temperature anisotropies in the CMB which show up as peaks in the spectrum. The 5 year power spectrum from the WMAP mission shows this in Figure 1.7.

The power spectrum in Figure 1.7 can then be fit by BB theory models and various cosmological parameters can be determined through the fit, for example $\Omega_B$, $\Omega_m$ and $\Omega_{tot}$ (mass density of the baryons - B -, matter - m - and the total universe - tot -). The second peak in the power spectrum of the CMB anisotropies determines the reduced baryon density $\Omega_B$ of the universe.

Combining results from the leading CMB experiments (WMAP, COBE, DASI, MAXIMA and BOOMERANG), the following values for the matter and total density parameters are given as [16, 17]:

\[
\begin{align*}
\Omega_b & = 0.02 \pm 0.002 & (1.1) \\
\Omega_m & = 0.26 \pm 0.03 & (1.2)
\end{align*}
\]
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Figure 1.7: Power spectrum of the CMB temperature fluctuations measured by WMAP as a function of multi pole moment $l$ (or angular size in degrees). The red curve is the $\Lambda CDM$ model predicted curve, which matches the data well [16].

\[ \Omega_{\text{tot}} = 1.02 \pm 0.002 \]  

(1.3)

It is already obvious here, that there is a large discrepancy between $\Omega_B$ and $\Omega_m$ as determined from the CMB. This would indicate that there is another, non-baryonic matter component in the universe that is needed to bridge this gap. This could of course be the dark matter. Another way to determine $\Omega_B$ to confirm these results is through BBN theory.
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BBN - confirmation of the theory and of CMB results

BBN refers to the time after the Big Bang when different light isotopes were created. It is thought that it took place a few minutes after the Big Bang and lasted until about twenty minutes after the Big Bang. BBN is thought to be responsible for the creation of D, He-3, He-4, Li-6 and Li-7. Also T, Be-7 and Be-8 were created, but since these isotopes are unstable they decayed shortly after their creation or fused with other nuclei to make other stable isotopes.

BBN began about one second after the Big Bang when the universe is cold enough to form stable protons and neutrons. Before this time, protons and neutrons are inter-converting and are also colliding to create deuterium (D) through the interaction $p + n \leftrightarrow D + \gamma$. At this time however, the density and energy of the cosmic background radiation (CBR) $\gamma$’s are very high and newly formed D are photo-dissociated by the high energy $\gamma$ rays. That means that before the D can capture a proton or neutron to form heavier nuclide’s, the D is photo-dissociated. This time period persisted until the temperature $T$ and density $\rho$ of the universe fell below values required for nuclear fusion. Since the BBN only lasted for about twenty minutes, heavier elements could not be formed.

The very important thing about BBN is that it lacks the speculative uncertainties associated with other theories of the early universe. This is the case because the physical laws and constants that describe the processes matter undergoes at these energies are very well understood. The theory of BBN gives precise quantitative descriptions of the primordial abundances of the isotopes mentioned above. This leads directly to the ability of BBN to make precise predictions about the contributions of these isotopes to the total mass of ordinary matter contained within a given region of the universe.

To confirm the existence of the BBN period after the Big Bang, the primordial
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abundances mentioned above need to be measured faithfully in experiments. The different isotopes can be measured using distinct approaches. Since the first stars formed, the abundances of light nuclei have been changing as the universe has undergone chemical evolution. Therefore, astronomical objects need to be identified in which the primordial abundances are preserved as well as possible, and any residual chemical evolution needs to be factored into those results. There are some indicators to measure this evolution, predominantly through the presence of oxygen and nitrogen. These elements are produced in nuclear fusion reactions in stars and not in BBN, so the more O and N are measured in a region of space, the more the abundances of the light isotopes have been influenced by stellar nuclear fusion. Two examples of how the abundances are experimentally determined are described below.

First a measure for the amount of He-4 shall be described. The abundance of He-4 is the most solid prediction of BBN, but from an experimental standpoint is much harder to measure, since He-4 is also a product of stellar nuclear fusion. To measure the primordial abundance of He-4, dwarf galaxies are the astronomical object of choice [18]. To search for the primordial He-4, dwarf galaxies that are especially poor in O and N are selected (meaning they have undergone minimal stellar nuclear fusion). Within the galaxies, astronomers look for HII regions, which are gas clouds mainly made up of protons and electrons. If this cloud is sufficiently hot, certain atomic reactions involving He atoms lead to characteristic emissions of electromagnetic radiation at frequencies that are precisely known. The intensities of these emission lines can then be compared to corresponding lines for H atoms and the abundance of He can be determined inside the cloud. The same method is used to measure the abundances of O and N in the cloud and infer the amount of chemical evolution undergone by the dwarf galaxy. All the measurements taken for different dwarf galaxies give a result of about 24% of He-4 abundance with an error of a little larger than 1%.
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The problem with measuring the primordial abundance of deuterium is, that it is only marginally stable and easy to destroy. For example, in stellar nuclear fusion processes, any D that might be present is quickly converted to He-3. Therefore, any abundance of D that is detected by astronomers, can only serve as a lower limit on the primordial abundance, but will have definitely been produced in BBN. The best values for measured D abundance is determined by looking at high-redshift quasars. Quasars are the nuclei of active galaxies and any light detected from these high-redshift quasars shows the universe at an age of about 10 billion years. The spectrum of these quasars can be analyzed using special absorption lines due to D and H and thus the D abundance can be determined. The current best value for the primordial abundance of deuterium is given as \((3 \pm 0.4) \cdot 10^{-5}\).

Now that the predictions and the experimental measurements have been discussed, the two can be compared. This is done in the plot in Figure 1.8. The Figure shows a plot of the number abundance of an isotope relative to hydrogen plotted versus the baryonic mass density \(\Omega_{B}h^2\) as introduced above. The solid curves indicate the theoretical predictions from BBN, and the horizontal stripes plot the values of the observationally determined abundances. The gray stripe going through the plot indicate the latest WMAP measurements of \(\Omega_{B}h^2\), which agree surprisingly well with both the observational and theoretical values for the abundances. Only the predicted value for Li-7 and the observed value are in larger disagreement. This is easily explained though, due to the uncertainties in the determination of the initial Li-7 abundance.

This result confirms, among other things, that BBN is a valid theory and gives fantastic results for deuterium and He-4 abundances. The important result taken from this though is the value for \(\Omega_{B}\), which, from the results presented above, is given by a value of \(\Omega_{B}h^2 = 0.02 \pm 0.002\) [19].

What this implies for the existence of dark matter, is that since there is a clear dis-
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Figure 1.8: The abundances of various elements relative to hydrogen. The solid lines describe theoretically modeled abundances and the horizontal bands give experimentally measured abundances. Where they intersect is the resulting $\Omega_B$, which is lower than the measured mass density $\Omega_m$. The best known abundance in the above picture is the deuterium abundance.

crepancy between the total value of matter density $\Omega_m$ given as $\Omega_m h^2 = 0.127 \pm 0.010$ and the baryonic matter density found to be $\Omega_m h^2 = 0.02 \pm 0.002$, the only explanation for this discrepancy seems to be the existence of another matter component, which is non-baryonic, making up about 20% of the universe. This different angle of looking at things therefore also requires a dark matter component to exist in the universe.
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1.2 One Dark Matter Candidate - WIMP’s

There are dozens of different theories for what the dark matter could be. This ranges from introducing new theories, like MOND, to the idea it could be made up of large baryonic objects yet to be discovered in the halos of galaxies. The Weakly Interacting Massive Particle (WIMP) is a novel, exotic particle and is considered the leading candidate for dark matter by many scientists.

WIMP’s are novel, non-Standard-Model particles, that only interact through interactions on the scale of the weak force or weaker. WIMP’s will also interact gravitationally. They are suspected to have a mass of 10GeV to a few TeV.

Since WIMP’s are particles that interact on the scale of or less strongly then the weak interaction, they should have been present at early times in the universe [?, ?]. Knowing this initial condition, the WIMP abundance in the universe today can be calculated and is very close to the actual measured abundance of dark matter in the universe today. This therefore already implies, that the weak scale is a promising mass scale for dark matter candidates. What this WIMP particle could be, still needs to be addressed [?].

One well motivated candidate for the WIMP is the lightest super-symmetric particle (LSP) in super-symmetric (SUSY) models. The most popular candidate from SUSY is the neutralino. It is the LSP in a number of different SUSY models and it would have the cosmologically required relic density. The beauty of considering the neutralino as the WIMP lies in the fact that SUSY was not designed to explain or account for dark matter in the universe. The neutralino would come naturally out of the theory, fulfilling all of the requirements for the WIMP. All of these considerations make the WIMP a compelling candidate for dark matter for many scientists. For a more detailed treatment of how the WIMP could be the LSP in SUSY models, refer to for example [20].
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For the purpose of all the discussions of dark matter in this Dissertation, the WIMP will be the only candidate considered and assumptions made about the possibility to detect the dark matter particle are only valid for WIMP dark matter.

1.3 Direct Detection of Dark Matter

The previous sections described how scientists came around to introducing dark matter, and how observational evidence supports these theories. All the evidence presented in the previous sections relies on “indirect” detection of dark matter. This means the dark matter is inferred from measurements that need dark matter to explain the observations. If the WIMP is indeed the particle that is making up the dark matter in the galaxy, it will have a small, but finite interaction with regular matter. It should therefore be possible to directly detect these dark matter particles on earth.

A direct dark matter detection would not only confirm the existence of dark matter, but furthermore allow for the study of the WIMP and its characteristics. A direct detection of the WIMP or a different dark matter particle is absolutely necessary for the understanding of physics today.

Various different detectors exist or a proposed to finally detect the WIMP directly on earth. They use different techniques to do so and it will not be clear which one is the best until an experiment detects a signal from a WIMP in their detector. The general principle of the WIMP interaction inside each of these detectors is the same. This is discussed in Section 1.3.1. The need for a so called “smoking gun” signature in this interaction is then discussed in the following two Sections. This will show how an unambiguous signature will underly the WIMP interaction inside a detector.
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1.3.1 WIMP nucleon scattering in a detector

When a WIMP interacts with a nucleus in any given detector, it will induce an elastic nuclear recoil. This recoil is what is then detected, either via ionization, scintillation or phonon signatures, depending on the detector used. It is important that the recoil energy and angle spectrum of the WIMP induced recoil is understood very well, such that a detector can be designed to exploit this signature as good as possible and use it to discriminate WIMP signals from background signatures.

In general the differential energy spectrum of the WIMP induced nuclear recoils is of the form [21]

\[
\frac{dR}{dE} = \frac{R_0 \cdot (m_x + m_n)^2}{E_0 \cdot 4 m_n m_x} \cdot \exp \left( -\frac{E \cdot (m_x + m_n)^2}{E_0 \cdot 4 m_n m_x} \right)
\]  

In this expression \( E \) is the recoil energy, \( E_0 \) is the mean kinetic energy of the incident WIMP, which has a mass of \( m_x \) \( (E_0 = \frac{1}{2}m_x v_{WIMP}^2) \). Also, \( R \) is the event rate per unit mass of target, \( R_0 \) is the total event rate, and \( m_n \) is the mass of the target nucleus.

When assuming the WIMP mass to be in the range of 10GeV to a few TeV and a WIMP velocity of \( 10^{-3} \) times the velocity of light, the expected recoil energy ranges would be about 1 to 100keV, depending on the target nucleus used.

The WIMP-nucleus scattering cross-section can also be determined. This cross-section can be calculated from Feynman diagrams using the minimum super-symmetric model (MSSM) framework from SUSY. Couplings of the neutralino with the quarks and gluons need to be considered for this and all of it is highly model dependent. This is the reason the cross section can not be exactly determined. In general it is known, that the WIMP nucleus scattering cross-section is proportional to the mass of the target nucleus, which means the heavier the target nucleus the larger the scattering cross-section. This might imply that using a heavy nucleus to detect WIMP’s is
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necessary, but that is not true. The recoil energy of a nucleus in an elastic scattering event is given as [22]:

\[ E_{\text{rec}} = 4 \cdot E_0 \cdot \frac{A \cdot \cos^2 \theta}{(1 + A)^2} \]  

(1.5)

with \( E_0 \) as defined above, \( A = \frac{m_x}{m_n} \) and \( \theta \) being the scattering angle in the laboratory frame of the interaction.

This shows, that for larger masses of the target nucleus, the recoil energy decreases. As every detector has a lower limit energy threshold, increasing the mass of the target nucleus in a detector might lower the recoil energy below this threshold and therefore make this detector not feasible for WIMP detection.

1.3.2 No background, direct detection

Most direct dark matter detection experiments today rely on the fact that they can run background free. Since a WIMP signature in a detector can mimic a background signature, it is important to first have a detector that can either run background free or that can identify all of the backgrounds in the detector as being from other particles such as neutrons or \( \gamma \) particles and not from a WIMP.

One example of one of the best direct detection experiments currently running with zero backgrounds is CDMS ("Cryogenic Dark Matter Search") [23]. The CDMS experiment uses Germanium and Silicon crystal substrates, run at temperatures on the order of milli-Kelvin to measure an ionization and a phonon signal for every event in the detector. This allows for particle discrimination between electron recoils and nuclear recoils. The CDMS detector currently holds the best limit for WIMP detection. This is shown in the exclusion plot in Figure 1.11 [24].
So far, every dark matter experiment, but one, has only published exclusion plots for direct dark matter detection. This means, that no experiment, besides one, has claimed to have actually detected dark matter. When this happens, a "smoking gun" signature of the dark matter signal needs to be measured to convince the scientific community that the detected signal is indeed a dark matter signal and not a background signal.

Two candidates for "smoking gun" signatures exist, one is the annual modulation of the WIMP signal and the other is "daily modulation" of the directional WIMP interaction in the detector. These two signatures are explained in the following two Sections.

1.3.3 Annual modulation of the WIMP signal

It is believed by many scientists that a smoking gun signature is needed to unambiguously detect the dark matter particle. The reasoning behind this statement is, that there is the possibility of mistaking a background event in the detector for a WIMP, since the interaction rates are so low. The first smoking gun signature of a dark matter particle in a detector is referred to as the "annual modulation" of the WIMP rate. The idea behind this detection mode is depicted in Figure 1.9.

It is assumed that the sun traverses through a stationary, homogeneous WIMP dark matter halo. It moves at a velocity of $v_0=230\text{km/s}$, which means in the rest frame of the earth, a WIMP would be detected with a velocity of 230km/s with a spread due to the thermal velocities of the WIMP’s. Since the earth itself rotates around the sun on a plane perpendicular to the motion of the sun and inclined at 60°, the velocity of the WIMP “wind” on earth would be affected as follows. In the summer (June), the earth has its largest velocity component parallel to that of the sun moving around the galaxy. This means that the velocity of the WIMP “wind”
Figure 1.9: The principle of the “annual modulation” signature of the WIMP. The sun moves through the galaxy and a stationary WIMP halo at a velocity $v_0$. Since the earth has its own motion around the sun, the velocity of the WIMP wind on earth will increase in June, due to a parallel velocity component of the earth’s movement and decrease in December. This changes the detection rate of the WIMP on earth $v_{WIMP,e}$ as detected on earth would be increased by this amount. In the winter (December), the earth has its largest velocity component anti-parallel to that of the sun. Again, this means $v_{WIMP,e}$ would be decreased by this amount.

To understand why this leads to a change in the detection rate of WIMP’s in the detector on earth, the interaction rate of WIMP’s in the detector is needed. This rate $R$ is given as [22]

$$R \propto \frac{N_T \rho_{DM} \sigma_0}{m_W m_n} \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} dv$$  \hspace{1cm} (1.6)

In this expression, $N_T$ is the number density of the target material used in the
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detector, $\rho_{DM}$ is the density of the dark matter in the halo that is traversed by the detector, $\sigma_0$ is the scattering cross-section of the WIMP with the target nucleus, $m_W$ and $m_n$ are the mass of the WIMP and the target nucleus and $f(v)$ in the integral is the velocity distribution of the WIMP’s in the halo. The integral runs from $v_{\text{min}}$ to $v_{\text{max}}$, where the minimum velocity detected is due to the finite energy threshold of any detector that limits the smallest energy that can be detected and the maximum velocity is due to the escape velocity of the WIMP’s from the galaxy. If their velocity was any larger than $v_{\text{max}}$, they would have escaped already and would not be in the halo of the galaxy any longer.

The integral in Equation (1.6) has been computed for many different assumed velocity distributions of the WIMP’s in the halo. The easiest distribution that can be chosen though, is that for a halo with an isotropic velocity distribution.

$$f(v) = \frac{\rho_0}{m_W \pi^{3/2} v_{\text{halo}}^3} e^{-v^2/v_{\text{halo}}^2}$$ (1.7)

Here, $v_{\text{halo}}$ is the velocity of the WIMP halo which will be chosen to be

$$v_{\text{halo}} = \sqrt{\frac{3}{2}} v_\odot \simeq (270 \pm 25) \text{ km/s}$$ (1.8)

This is only true if the halo distribution function of the WIMP’s is proportional to $r^{-2}$. This function needs to be further converted to the lab frame where it is given as

$$f(\vec{v} + \vec{v}_\odot + \vec{v}_{\text{earth}}) = \frac{\rho_0}{m_W \pi^{3/2} v_{\text{halo}}^3} e^{-v^2/v_{\text{halo}}^2}$$ (1.9)

Inserting Equation (1.9) into the complete Equation for the scattering rate found in [22] (Equation (1.6) is simplified from that), the expression for the interaction rate with respect to energy $E$ and scattering angle $\gamma$ is given as:

$$\frac{dR}{dE d\cos\gamma} = \frac{\rho_0 \sigma_0}{\sqrt{\pi}} \frac{(m_W + m_n)^2}{2 m_W^2 m_N v_{\text{halo}}} \cdot \exp \left[ -\frac{[v_E + v_\odot\cos\gamma - v_{\text{min}}]^2}{v_{\text{halo}}^2} \right]$$ (1.10)
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Using this equation the difference between the scattering rate in June and December can be computed.

Since \( v_{\text{min}} \) differs for different experiments, various values of \( v_{\text{min}}/v_{\text{halo}} \) can be used to compute different values of \( R \). Other variables that need to be used as well are \( v_{\text{earth},||}=15\text{km/s} \), \( v_\odot=230\text{km/s} \) and \( v_{\text{halo}}=270\text{km/s} \).

Using these numbers and assuming a reasonable detection threshold this effect is expected to yield an effect of about 4% difference in the interaction rates in the detector on earth. This is a rather small number and a positive detection of this result might not be very convincing. This is exactly what has happened in the case of the DAMA (DArk MAtter) collaboration and their claimed positive result.

The DAMA collaboration had first claimed a positive detection of this annual modulation effect in 2002 [25]. This claim has been repeated in 2008 with smaller error bars and larger statistics [26]. A plot of the residual detection rate vs time in days is shown in Figure 1.10. It can be seen that the residual rate oscillates in a sinusoidal fashion around zero and with an almost perfect frequency of a year. The problem with this result is the range in which the mass and scattering cross-section of the WIMP would have to fall has been excluded by various other experiments. This can be seen in on the left hand side of Figure 1.11. The DAMA result is shown and the exclusion plots from Edelweiss ruling out the positive detection claimed.

The positive detection by DAMA and the nonexistence of an explanation for the result other than dark matter is a big controversy and needs to be resolved. The only way to really convince the broader community would be with a second positive detection of WIMP dark matter in a second experiment. This would probably be most convincing if the second detection was made using a different approach for dark matter detection. This is why the second smoking gun signature is needed, which is described in the following.
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Figure 1.10: The annual modulation as detected by the DAMA collaboration [26]. The plot shows residual detection rate versus time in days. This plot shows the result for different energy ranges in keV/amu. These plots are combined results from the DAMA/NaI and DAMA/LIBRA detectors.
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Figure 1.11: Two exclusion plots, plotting the cross-section for WIMP versus the WIMP mass in GeV/c². The plot on the left shows the region DAMA has claimed for WIMP detection and preliminary EDELWEISS data from the year 2002, ruling out this region. The plot on the right shows the latest CDMS results [24]. This plot shows how far below the DAMA result in the exclusion plot current experiments are, making the positive DAMA detection a puzzle scientists have not been able to explain yet.

1.3.4 Daily “modulation” of the WIMP signal

The daily modulation describes the change of the direction of WIMP induced nuclear recoils in a detector during the course of one sidereal day. A cartoon of the principle behind the daily modulation is shown in Figure 1.12.

This particular signature of the WIMP in the detector, is due to the rotation of the earth around its own axis with a period of $T_{\text{earth}} = 23\text{h\,56min}$, while moving around the sun. This means, a detector positioned for example at the Boulby mine, will be at about 42° from the earths rotational axis (see Figure 1.12. Since the WIMP
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Figure 1.12: The daily “modulation” of the WIMP induced nuclear recoils in a dark matter detector is shown here. At 12am of a given day the recoils in the detector will point predominantly toward the center of the earth and 12 hours later, at 12pm they will point in a direction perpendicular to the earth’s axis. This effect can be used to distinguish a WIMP signal from a background signal.

induced nuclear recoils will scatter predominantly in the forward direction, away from the WIMP wind, at 12pm, the recoils will be pointing in a direction perpendicular to the earth’s surface, or awards one of the sides of the detector. At 12am, the recoils will point awards the center of the earth, or in this case the bottom of the detector. When plotting the recoil angle of the expected WIMP-nucleon scattering angle in a fixed coordinate system (fixed with respect to the dark matter detector for example) over the course of a day, the recoil angle changes over this period, which is why this signature is also referred to as a daily modulation signal. If a background signal would mimic the WIMP signal in the detector, the recoil angle would be randomly distributed in space and therefore could not mimic the signal expected from WIMP’s.

To illustrate how the scattering due to WIMP’s is different from scattering due to randomly distributed background events, the scattering angle is defined as $2\pi - \gamma$. Here $2\pi - \gamma$ is the angle between the nuclear recoil and the direction of the sun’s motion. This is shown in Figure 1.13.
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Figure 1.13: Definition of the scattering angle for directional detection of WIMP’s. The incoming WIMP is somewhat aligned with the motion of the sun around the galaxy.

When plotting this angle for WIMP recoils, it is expected to be peaked around $\gamma=0$. The expected scattering angle $\gamma$ found from simulations [27], is plotted in Figure 1.14.

The plot on the top of Figure 1.14 shows the angle distributions if only three dimensional tracking is available and the bottom plot shows the distribution if full 3D vector tracking is possible. It can be seen here already, that the full 3D vector track gives a much larger effect in the distribution of the recoil angle, therefore less events would be needed to know that the distribution is not isotropic (if the events were due to background events, the recoil angle distribution would be flat across all angles $\gamma$).

To measure the direction of the recoiling nucleus, the track created by it needs to be resolved. This is only possible if the track is long enough. It was mentioned before, that the expected recoil energy from a WIMP interaction is on the order of 1 to 100keV, which is very low energy. This in turn means that the track lengths are very short. Due to this peculiarity, this directional signature of the WIMP
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![Figure 1.14: Definition of the scattering angle for directional detection of WIMP’s. The incoming WIMP is somewhat aligned with the motion of the sun around the galaxy.]

The interactions can only be resolve in a low pressure, gaseous detector.

The number of events needed to attribute a directional signature in a gaseous detector to a WIMP interaction is strongly dependent on how well the three dimensional track can be reconstructed and if a vector direction can be assigned to it. Detailed studies of the effect this has on the number of WIMP interactions in the detector needed have been performed in [28, 29]. It can be generally said, that if the nuclear recoil can be reconstructed in three dimensions but will have the degeneracy in the vector direction on the order of 100 events are needed to claim WIMP detec-
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ation. If the vector sense can be assigned, on the order of 10 events would be needed, which is a significant improvement, considering that the WIMP interaction rates are so low.

How the three dimensional vector track can be reconstructed in a gaseous detector is described in Chapter 2, Section 2.4.
Chapter 2

Generation of tracks in a gaseous detector - WIMP interactions

How nuclear recoil tracks are formed inside a gaseous detector, in particular a gaseous detector using CS$_2$, is described. The only currently operating directional dark matter detector DRIFT is introduced. The detector is described briefly and it is explained how the particular prototype detector described in this Dissertation is used to investigate the fundamental nature of low energy nuclear recoil tracks from WIMP interactions. How well this detector will be able to investigate these fundamental properties is described as well.

2.1 The DRIFT detector

The DRIFT (= Directional Recoil Identification from Tracks) collaboration consists of member institutions in the US (Occidental College, Los Angeles and University of New Mexico, Albuquerque) and the UK (University of Sheffield and University of Edinburgh) and operates a dark matter detector in the Boulby mine in the UK. The
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science goal of the DRIFT detector is to measure the directional signal of the nuclear recoils induced in the detector by WIMP nucleon interactions (see Section 1.3.4 for more detail). The current detector module that is operational underground in the Boulby mine is DRIFT-IIb. Former DRIFT modules were used underground prior to the current one and details about them and results from the runs can be found in [30, 31, 32].

The DRIFT detector is based on the idea of the Negative Ion Time Projection Chamber (NITPC) [33]. This means, it uses the principal of a Time Projection Chamber (TPC) with an electronegative gas mixture, Carbon disulfide (CS$_2$). A schematic of the principle of the DRIFT operation is shown below in Figure 2.1.

![Figure 2.1: The principle of operation of a DRIFT module.](image)

A TPC is an ionization detector that is capable of three dimensional tracking and can provide various information. It can provide spatial information on a track with very high resolution and measures the specific energy loss dE/dx of a particle.
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Usually a TPC consists of a gas or liquid filled detector volume with a cathode on the top and a readout plane attached in the bottom of the chamber which would provide for signal readout. An electric field is applied between the cathode and the readout such that the primary charge carriers are transported from the detector volume to the readout planes. Since in regular TPC electrons are the charges that will be readout, a magnetic field parallel to the electric field is applied as well. The magnetic field confines the electrons to helical trajectories about the drift distance. This will limit the electron diffusion dramatically, but special care must be taken in the alignment of the magnetic field to avoid deviating the the trajectories of the drifting electrons.

As mentioned above, DRIFT uses a electronegative gas. The result of this, which can be seen in Figure 2.1, is that the electrons which are created as ionization when a particle interacts in the drift volume, will readily attach to the \( \text{CS}_2 \) molecules, creating negatively charged ions \( \text{CS}_2^- \). These will then be drifted to the readout plane in the electric field. The reason to drift negatively charged ions instead of electrons, is the minimization of diffusion without the need to apply a magnetic field. The exact mechanism that allows for this is described in detail below in Section 2.4.2.

The readout plane in the DRIFT detector employs Multi wire Proportional Chambers (MWPC). There are two MWPC’s on each end of a DRIFT module. The operation principle of a MWPC is quite involved and has been discussed elsewhere (see for example [34]). To give the basic operating principle, an MWPC consists of a plane of equally spaced (in DRIFT the spacing is 2mm) anode wires centered between two cathode planes. The gap between the anode and cathode planes is \( x \) mm in DRIFT. A negative voltage is then applied to the cathode plane, which will create field lines going from the cathodes to the anode wires. These field lines will be mostly parallel and straight except for a region very close to the anode wire region. Here the field takes on a \( 1/r \) dependence, which is similar to the single wire cylindrical proportional
chamber. If electrons and ions are liberated in the constant field region inside the detector volume, they will drift along the field lines to the nearest anode wire and opposing cathode. Since negative ions are drifting in DRIFT, they will drift towards the closest anode wire. When entering the high field region around the wire, the electrons will be easily stripped off the CS$_2$ molecule and start avalanche multiplication as described in Section 2.3. In this process positive ions are liberated which will start drifting towards the cathode wires in the MWPC and in the process induce a negative signal on the anode wire. This is the signal seen on the wire, it is not created by the electrons collected in the process as one might think. The anode plane is used to reconstruct information in the X dimension of the detector. In DRIFT, the first cathode plane of the MWPC is integrated as a readout plane as well, the grid. When the liberated positive ions drift towards the grid, they will also induce a signal here and allow for information in the Y dimension to be collected.
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The anode and grid wires are all readout using Amplifier and shaping electronics. Not every wire is readout individually, since that would create too many channels, increasing the price of the electronic components significantly. This problem is easily solved, every eighth wire is combined and readout through the same readout electronics. The number of wires was chosen at eight, because no track that would be interesting for dark matter searches will be longer then eight wires or 1.6cm. This way, a lot of money can be saved in the construction of a DRIFT module and the complexity of the analysis used is also greatly decreased.

The dimensions of all DRIFT modules are 1m x 1m x 1m with the MWPC’s sitting at two opposite planes of the detector. A central cathode constructed from stainless steel wire is mounted half way in between the MWPC’s. The MWPC’s themselves are made from x μm stainless steel wire.

A photograph of the DRIFT detector when it is outside of the vacuum vessel is shown in Figure 2.2. The MWPC can not be seen, but they are located where the two blue stripes are on the outside of the cube. The blue strip in the center marks the position of the central cathode that can also not be seen, since the wires are just too small.

The entire DRIFT module as seen in the photograph is then inserted into a stainless steel vacuum vessel. The detector is operated at 40torr pressure, to allow for increased track lengths that can be resolved as discussed previously. The CS₂ gas used is continuously flown through the detector at 40torr, to keep the gas as clean as possible and suppress contamination of the gas with either Radon, which would introduce background signals or H₂O, which would decrease the pulse height of the signals due to electron capture.

More detail on the operational principle of DRIFT and the construction details can be found for example in [31].
2.2 Drift of $e^-$ and charged ions in gases

To explain why DRIFT uses a negative ion gas to drift the charge to the readout plane and does not simply employ electron drift, the different scenarios contributing to the drift of $e^-$’s and ions in a gas need to be understood.

The drift of electrons shall be described first. When electrons move in an electric field $E$ in a gas, they will suffer random collisions with the gas molecules. This limits the maximum average velocity that can be attained by them in the gas. This is known as the drift velocity. This drift velocity is superimposed on top of the thermal velocities, which for electrons can be much higher then the drift velocity. The number of collisions $dn$ that an electron undergoes in the gas when moving a distance $dx$ is

$$dn = \frac{1}{v \tau} dx$$  \hspace{1cm} (2.1)

Here $v$ is the velocity of the electron and $\tau$ the average time between collisions, which is inversely proportional to the density of the gas $N$ and the instantaneous electron velocity $v'$. $1/\tau$ is also referred to as the collision rate and is related to the just mentioned variables as

$$\frac{1}{\tau} = N \sigma v'$$  \hspace{1cm} (2.2)

Here $\sigma$ is the cross-section for the collision of the $e^-$ with a gas molecule. The time between collisions is also determined by the probability of a collision taking place, $dP$, which in a time interval $dt$ is given as

$$dP = \frac{1}{\tau} e^{-\frac{t}{\tau}} dt$$  \hspace{1cm} (2.3)

Since the electron is moving in an electric field $E$, it is accelerated between colli-
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sions according to

\[ m \frac{dv}{dt} = q_e E \]  

(2.4)

Here \( m \) and \( q_e \) are the mass and the charge of the electron. It is also important to know the electron’s displacement versus time, which is found by integrating Equation (2.4):

\[ x(t) = \frac{1}{2} \frac{q_e}{m} E t^2 \]  

(2.5)

By integrating \( x(t) \) over time and using the collision probability as defined in Equation (2.3), the average displacement \( < x > \) can be found as

\[
< x > = \int_0^\infty x(t) \frac{dP}{dt} \, dt \\
= \int_0^\infty \frac{1}{2} \frac{q_e}{m} E t^2 \frac{1}{\tau} e^{-\frac{t}{\tau}} \, dt \\
= \frac{q_e}{m} E \tau^2 
\]  

(2.6)

(2.7)

(2.8)

From this the average drift velocity can be calculated:

\[
< v > = \frac{< x >}{\tau} = \frac{q_e}{m} E \tau \equiv \mu E 
\]  

(2.9)

The last expression defines the mobility of the electrons \( \mu \) as

\[
\mu \equiv \frac{q_e}{m} \tau 
\]  

(2.10)

As shown before, \( \tau \) is inversely proportional to the density of the gas, which is equivalent to the pressure, the drift velocity is proportional to the electric field \( E \) divided by the pressure \( p \) of the gas.

\[
< v > \propto \frac{E}{p} 
\]  

(2.11)
Using this information, the average velocity, or drift velocity, of the electrons in a gas is commonly written as

\[ v_{\text{drift},e} = \mu E \frac{p_0}{p} = \mu p_0 \frac{E}{p} \]  

(2.12)

Here \( p_0 \) is the standard pressure and is used since \( \mu \) is determined at that value.

There is one problem with this derivation though. This is that the collision cross-section for electrons is not constant over all fields \( E \), but is energy dependent. So the simple relation that has just been derived does not hold for the full range of fields for electrons.

The same derivation as shown for electrons holds for ions as well. Since the ions are very massive, the collision cross section discussed above does remain constant over all ranges of electric field though. Therefore, the drift velocity for positively (+) or negatively (-) charged ions is given as

\[ v_{\text{drift},+/-} = \mu^{+/-} p_0 \frac{E}{p} \]  

(2.13)

As an interesting fact, comparing the drift velocities of ions and electrons in the same gas mixtures, the drift velocity of the ions in a 1000V/cm electric field is about 1000 times smaller than the electron drift velocity.

### 2.3 Avalanche Multiplication of the primary charge in a gaseous detector

Since the primary charge usually consists only of a few free charges, a multiplication stage is needed in the detector to proportionally increase the amount of ionization such that it can be detected. Various schemes for multiplication exist, but they all
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involve a region of high electric field to achieve avalanche multiplication. In DRIFT Multi Wire Proportional Counters (MWPC) are used and the detector used for the work presented in this dissertation uses the Gas Electron Multiplier (GEM) which is discussed in detail in Section 3.1. Some detail will be given in the following about how the high field region in these devices causes avalanche multiplication.

When the primary ionization enters a high field region, for example around a wire in a MWPC, it will gain large amounts of energy from the accelerating fields to ionize further gas molecules. These secondary electrons will themselves accelerate in the electric field and cause tertiary ionization and so on. This creates an avalanche, which due to the greater mobility of the electrons, will have the shape of a liquid drop the the electrons grouped near the head and the slower ions trailing behind. This concept can be seen in Figure 2.3.

![Avalanche Multiplication Diagram]

Figure 2.3: The principle of the process of avalanche multiplication in a gaseous detector [34].
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As introduced before, $\lambda$, the mean free path of the electrons (now in the high field of the multiplication region) is related to the probability of an ionization per unit path length as

$$\alpha = \frac{1}{\lambda}$$  \hfill (2.14)

This is also known as the first Townsend coefficient and they are obviously different for different gases.

If at a given time, $n$ electrons are moving a path $dx$, the number of new electrons $dn$ created is given as

$$dn = n\alpha dx$$  \hfill (2.15)

This can be integrated to achieve the total number of electrons created in a path $x$, which will be given as

$$n = n_0e^{\alpha x}$$  \hfill (2.16)

where $n_0$ is the number of electrons in the primary ionization before avalanche multiplication happens. The gain factor of the gas in the avalanche region is then given as:

$$G = \frac{n}{n_0} = e^{\alpha x}$$  \hfill (2.17)

This is only true for uniform electric fields. Usually in the multiplication devices such as the MWPC or the GEM, the field is non-uniform and the gain will be given as

$$G = e^{\int_{x_1}^{x_2} \alpha(x)dx}$$  \hfill (2.18)
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Since knowledge of the gain factor in a proportional counter is very important, many theoretical models have been developed to calculate $\alpha$ for various gases. Many of these theoretical models can be found in [35].

2.4 Measuring a vector recoil in three dimensions

It has been discussed in Section 1.3.4 that it is crucial for a directional experiment to measure the WIMP induced, three dimensional nuclear recoil track including its vector direction. This is important to decrease the number of events needed for a positive identification of a WIMP signal. The ability to reconstruct a three dimensional track is of course important, which mainly depends on the detector setup. The possibility to reconstruct the vector direction of the recoil might as well depend on the detector setup, but is first of all dependent on the available track information that will allow for its determination.

To allow for a vector sense to be assigned to a recoil, the ionization created along a recoil track can be used. This ionization is expected to be asymmetric with either more charge in the beginning or the end of a track. If this asymmetry exists and can be measured, the vector direction can be assigned to the recoil as well. To discuss the existence of this asymmetry, the theory of stopping of ions in material is described below as well as the limitations of the detection of such an asymmetry

2.4.1 Stopping of ions in material

When a WIMP or a neutron scatters elastically off a target nucleus (Carbon or Sulfur), it transfers the amount of energy to the nucleus shown in Equation(1.5).
The recoiling nucleus will then move through the gas, losing its energy in electronic and nuclear collisions with the atoms in the gas [36]. The electronic collisions are due to interactions with the atomic electrons only. They will create ionization, scintillation and heat along the recoil track. The nuclear collisions lead to a recoil of the atom that was hit, which is also referred to as a secondary recoil. The nuclear collisions therefore create heat. Nuclear stopping is usually a factor of $10^3$ smaller then the electronic stopping component [36].

In general the energy loss of a particle in a material is shown in a Bragg curve. A sample Bragg curve [36] is shown in Figure 2.4.

![Bragg Curve](image)

**Figure 2.4:** Sample Bragg curve illustrating the energy loss of a particle in a medium [36].

The Bragg curve shown here is not a measured one for a particular ion but instead illustrates the general behavior of the energy loss for decreasing velocities or energies.
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The specific Bragg curves for different ions differ significantly from one another.

The different regions of the Bragg curve, as indicated in Figure 2.4, are as follows:

- **Region I**: This region corresponds to high velocity ions moving through matter. The energy of these ions is between 10MeV/amu and 2GeV/amu, for higher energies relativistic corrections become important. Due to their large velocity, the ions are completely bare, meaning they have lost all their electrons. In this case dE/dR increases with decreasing velocity. In this region, the energy loss is well described by the Bethe-Bloch formula [37].

- **Region II**: This region of the Bragg curve corresponds to the case where the velocities are intermediate and the ions are not completely stripped of their electrons. These electrons partially screen the field of the nucleus. This leads to the stopping being below the Bethe-Bloch expression. This region of the Bragg curve is not very well described theoretically for heavy ions, since corrections need to be made. The arrow with the label “shell corrections” in the Bragg curve refers to atomic inner shell corrections that can be introduced to the Bethe-Bloch treatment for ions with low Z [38], [39].

- **Region III**: This is the low velocity (low energy) region of the Bragg curve. The ion velocity is less then \( v = v_0 Z^{2/3} \) with \( v_0 = \frac{e^2}{\hbar} = c/137 \) [40]. Due to this low velocity, the ion is to a large extent neutralized by its electrons. The complications in this region arise for the same reasons as mentioned in Region II and are also due to the fact that at these very low velocities nuclear stopping will actually compete with electronic stopping. This means the effects are much harder to study and measure.

It becomes clear, that, for the low energy nuclear recoils of interest to direct dark matter detection, the region of interest is Region III of the Bragg curve. This is
clearly the least studied regime of the Bragg curve. More precisely, it is unknown in this region how the curves of electronic and nuclear stopping behave at these low energies.

Two curves illustrating the nuclear and electronic components of the stopping of ions in material is shown in Figure 2.5 [40].

![Graph of nuclear and electronic stopping curves](image)

Figure 2.5: Expected nuclear and electronic stopping curves for low energy nuclear recoils [40]. On the x axis the square root of the ion energy is plotted which is proportional to the velocity and the y axis is in units of dE/dR. The straight, dashed line indicates the standard stopping cross section $S_n^0$ (see [40]). These curves were computed using basic assumptions and treating the nuclear collisions classically. These curves were not computed to a high level of accuracy but instead to illustrate the expected effects.

It can be expected that the electronic stopping, which creates the ionization, decreases linearly with decreasing velocity of the ion. The unknown is the nuclear stopping. In general, the energy from nuclear stopping is lost in heat and can not
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be detected in a DRIFT like detector. The secondary nuclear recoils created in the process of nuclear stopping might also be able to create ionization along their path. If this is the case, the ionization detected along a track might not be falling linearly with the decreasing velocity of the ion.

The stopping power $\frac{dE}{dx}$ in material can also be described by the following equation [41]:

$$\frac{dE}{dx} = k_1 \frac{(\gamma z)^2}{\beta^2} \frac{Z}{M} [L(\beta, (\gamma z), Z) + \Delta L_r(\beta)] \quad (2.19)$$

Here, $k_1$ is a constant defined as $k_1 = 3.072 \cdot 10^{-4}$, $Z$ is the atomic number of an atom of the medium that the ion is moving through, $\gamma z$ is the net charge of the ion (if the ion is almost neutral, $\gamma$ will tend to zero) and $\beta$ is equal to $v/c$, with $v$ being the velocity of the moving ion. $M$ is the rest mass of an atom in the material medium and $m$ is the rest mass of the ion. The last term in Equation (2.19), $\Delta L_r(\beta)$, is a relativistic correction to the stopping power and can be neglected for the slow moving ions of interest.

The problem why this equation is not solved at low velocities is, that it is unknown how the quantity $\gamma$ and the function $L$ depend on $Z$, $M$, $z$, $m$, and $v$. This is unknown for the low velocities of interest and the stopping power can not be calculated analytically.

The theory of stopping ions in material might therefore not be able to assure the existence of an ionization asymmetry along a recoil track, but certainly gives good indication that it should exist. This asymmetry, if following the expected curve should lead to larger amounts of charge in the beginning of a track than at the end of a recoil track. It is important to measure this effect to confirm this assumption and give an indication to theorists how the Bragg curve behaves at low energies.

Even when assuming that a charge asymmetry exists, it still needs to be shown
that it is large enough to be measured and that the effect is not removed by the
detector setup used or the measurement techniques. Possible effects that could wash
out such an asymmetry effect are discussed in the following Sections.

2.4.2 Electron and Ion diffusion in a gas

Diffusion of the primary charge carriers in the detector can lead to the ionization
asymmetry of a low energy nuclear recoil track to be washed out. It is therefore
important to understand the size of the diffusion in the detector at hand. This is
done in the following.

When electrons or ions are created at one point in a gaseous detector with no elec-
tric field applied, they will experience diffusion outward from their point of creation.
The transverse diffusion will spread the charge radially according to a Gaussian dis-
tribution, which after letting the charges diffuse for a time $t$ will be given as

$$n(r) = \left( \frac{N_0}{\sqrt{4\pi Dt}} \right)^3 e^{-\frac{r^2}{4Dt}} \quad (2.20)$$

Here $N_0$ is the total number of charges diffusing, $r$ is the radial distance from the
point of creation and $D$ is the diffusion coefficient. $D$ is defined as

$$D = \frac{1}{3} v\lambda \quad (2.21)$$

with $\lambda$ being the mean free path of the electron or ion in the gas, which is given for
a classical ideal gas as

$$\lambda = \frac{kT}{\sqrt{2}P\sigma} \quad (2.22)$$

with $P$ being the pressure of the gas and $\sigma$ is again the collision cross-section.
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From Equation (2.20), the RMS spread after drifting a distance $x$ is found to be

$$\sigma(x) = \sqrt{2Dt} \quad (2.23)$$

and in three dimensions as

$$\sigma(r) = \sqrt{6Dt} \quad (2.24)$$

Inserting the expression for $\lambda$ into Equation (2.21) and assuming that the velocity of the charge carriers in the case of no drift field $E$ being present is given as $v = \sqrt{\frac{kT}{\pi m}}$, $D$ can be written as

$$D = \frac{2}{3\sqrt{\pi P}\sigma} \sqrt{(kT)/m} \quad (2.25)$$

It can be seen here that the diffusion is inversely proportional to the pressure of the gas $P$, the collision cross-section $\sigma$ and the mass of the particle diffusing.

If now an electric field $E$ is applied the charges will drift with a velocity $v_{\text{drift}}$ while diffusing as described above. The mobility introduced in the previous section can also be related to the diffusion coefficient via the so called Einstein relation

$$\frac{D}{\mu} = \frac{kT}{e} \quad (2.26)$$

Combining this equation with the relationship $\mu = v_{\text{drift}}/E$ yields

$$D = \frac{v_{\text{drift}}kT}{Ee} \quad (2.27)$$

This means, that the diffusion will decrease with increasing electric field. The reason this is true, is that the ions or electrons will be accelerated more along the field lines and therefore decrease the effect of the diffusion due to their thermal velocities.
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It is also important to know how the diffusion changes with the drift distance $L$ of the charge carrier, which in the detector would be the distance between where they were created to the readout plane. Considering that the drift time can be calculated as

$$t_{\text{drift}} = \frac{L}{v_{\text{drift}}} = \frac{L}{\mu E} \quad (2.28)$$

and using the so called electron energy $\epsilon = \frac{3De}{2\mu}$, the spread of the diffusion from Equation (2.23) can be rewritten as

$$\sigma^2(L, E) = 2Dt = \frac{2DL}{\mu E} = \frac{4\epsilon L}{3eE} \quad (2.29)$$

If ions are drifting, the electron energy $\epsilon$ is at most in the thermal limit and given as $3/2kT$. For electrons on the other hand, $\epsilon$ varies from the thermal case of $3/2kT$ at low electric fields to several eV at higher $E/p$. This would make the diffusion very large for electrons and is the reason magnetic fields are used in a TPC to minimize electron diffusion as described above. In the following, only ion drift is considered since the case for not using electron drift has been made here, and DRIFT uses negative ions as charge carriers anyways.

Using $3/2kT$ as the electron energy $\epsilon$, the diffusion can be simplified to

$$\sigma^2(L, E) = \frac{2kT L}{e E} \quad (2.30)$$

The first factor in this equation can be calculated for room temperature (operation temperature of DRIFT as well as the here described prototype) and rearranging units, gives the

$$\sigma(L, E) = 720\mu m \sqrt{\frac{L}{m} \frac{1kV/cm}{E}} \quad (2.31)$$
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It is interesting to note here, that this relation does not depend on the gas used, only on the electric field and the drift length. This is of course only true for positive or negative ions drifting in a gas.

For the DRIFT detector, the maximum length charges will drift is 50cm and the field is 0.58kV/cm. This leads to a maximum diffusion of

$$\sigma_{\text{DRIFT, max}} = 720 \mu m \sqrt{0.5 \frac{0.5}{0.58}} = 669 \mu m$$

(2.32)

In the prototype detector described in Chapter 3, the maximum drift distance is 2cm in an electric field of 700 V/cm. This will lead to a maximum width of the diffusion of

$$\sigma_{\text{prot, max}} = 720 \mu m \sqrt{0.02 \frac{0.7}{0.7}} = 122 \mu m$$

(2.33)

This is a very small amount of diffusion that should not remove any asymmetry in the ionization along a recoil track. A second diffusion is introduced in the detector as well. The size and effect of this diffusion is discussed in detail in Chapter 6.

2.4.3 Straggling in low energy nuclear recoil tracks

Another problem that might increase the difficulty of measuring a charge asymmetry along a recoil track is due to straggling. Straggling refers to the fact that recoil tracks at the low energies introduced above are not straight. On the contrary, they are usually spread out in various different directions and might even curl up on themselves. An example of the straggling of these recoils is shown in Figure 2.6 [42].

Shown in this picture are 10 simulated Carbon and Sulfur recoils moving through 40torr CS₂. It can be seen that the Carbon recoils are much more straight then the Sulfur recoils and create not as many secondary recoils.
Figure 2.6: Simulation of the straggling observed in 100keV Carbon (on the left) and 100keV Sulfur (on the right) recoil tracks. The red line shows the recoil track taken by the C or S ion (10 recoils were simulated in each case) and the blue lines show secondary recoils of either C or S [42]

The problem with the straggling is due to the “balling up” of charge in the end of the track. How this might effect the ability to measure a charge asymmetry on a recoil track is depicted in Figure 2.7.

When a track is curled up in the end, even though there might be less charge in the end of a track, due to the high concentration of the track in the end, it might look like there is the same amount of charge in the end of the track as in the beginning. This would mean that a distinction between the front and the back of a track is not possible.

This chapter has shown that the measurement of an ionization asymmetry along a nuclear recoil track is needed to determine the three dimensional vector direction of a nuclear recoil. This asymmetry is expected to exist, but diffusion and straggling might make it much harder to detect. It can not be predicted at this point if the measurement of the charge asymmetry is possible, which is why the measurement
Figure 2.7: Schematic showing the effect straggling has on the ability to detect an asymmetry in the charge distribution along a nuclear recoil track. When there is less charge in the end of the track, but the track is curled up as shown, in the detector plane, the same amount of charge might be measured in the beginning of the track as at the end.

needs to be made with the prototype detector. If with a high resolution detector, the measurement is not possible, DRIFT will also not be able to determine the vector direction.
Chapter 3

Detector Setup

In this chapter, all of the components of the experimental setup will be described. First, the individual components used in the detector setups are introduced. Two different detectors were used, one using a one dimensional readout board (1D) and the other using a two dimensional readout board (2D), the different components for each are explained separately. In the end of this chapter, the detector setups in their entirety are described and it is explained how all the parts are fit together to form the final prototype detector setup.

3.1 The Gas Electron Multiplier (GEM)

To multiply primary charge carriers created in the target gas of the detector, a multiplication stage is needed. It was decided to use Gas Electron Multipliers (GEM) for this stage, which were purchased from the CERN “Gas Detectors development group” [43].

The GEM was invented by F. Sauli at CERN in 1996 [44] and is made up of a 50µm thick sheet of Kapton that is sandwiched between two 5 µm thick sheets
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of copper. Holes of 70µm diameter are chemically pierced through this sheet. The pitch of the holes is \( \approx 140 \, \mu\text{m} \). A microscopic view showing the holes through the GEM is shown in Figure 3.1.

![Microscopic view of GEM holes](image)

**Figure 3.1:** The picture on the left shows a microscopic picture of the GEM holes. The holes pierced through the surface can be seen. The picture on the right shows the electric fields inside the GEM holes when a potential difference is applied across the GEM generated with Maxwell [45].

To operate the GEM, a potential difference is applied between the top and the bottom copper surface. This creates a very large electric field inside the GEM holes. A plot of the field lines inside the GEM holes generated with the simulation package MAXWELL [45] is shown on the right side of Figure 3.1. When a certain amount of charge is created above the GEM, the charge will drift towards the holes, avalanche multiply and transfer into the region below the GEM where the charge can be collected. The secondary charge below the GEM will be larger than the initial charge by a gain factor given as

\[
G_{GEM} = \frac{q_{\text{secondary}}}{q_{\text{primary}}} \tag{3.1}
\]

Each hole of the GEM therefore acts as an individual proportional amplifier.
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The GEM can be used as a detector on its own, or as in the case for this dissertation, as the amplification stage in a complex detector structure. One of the advantages of the GEM is, that if larger gains are needed, the GEMs can be easily stacked on top of one another (see for example [46]). Another advantage is that it allows the separation of the amplification stage of the detector from the readout stage. This allows for safer operation at high voltages and gives a greater freedom to choose the best readout scheme for each detector situation. Detailed studies of gains and discharge points of GEMs in various gases have been performed elsewhere and a couple of different references are given here [47, 48, 49, 50].

A picture of a regular, framed copper GEM is shown in Figure 3.2. The points where the high voltage is connected to the top and the bottom of the GEM can be seen on the left side of the GEM in the picture. This GEM is representative of the ones used in the detector setups described below. Besides the regular Copper GEMs, custom, Gold coated GEMs were also used in some of the data taking runs. These GEMs were used since it was thought that the CS$_2$ could potentially damage the Copper surfaces. This was not the case and since both kinds of GEMs performed in the same way, both were used in the measurements presented.

The common 10cm by 10cm GEMs were only used in the 1D detector setup. Due to size constraints on the 2D readout board, custom 7cm by 7cm GEMs were used in this case. How the GEMs were operated in the detectors used is described later on in Section 3.7.

3.2 The Readout Boards

Two different kinds of readout boards are used in the detector. A one dimensional readout board was used initially and a two dimensional readout board was used in the later stages.
Figure 3.2: A typical GEM used in the detector setups described below. The GEM shown is made out of copper, was pre-framed by CERN and had dimensions of 10cm by 10cm.

### 3.2.1 1D readout board

The one dimensional readout board has 16 strips in one direction referred to as X strips. They are made out of Copper and were manufactured at the electronics shop at UNM on a printed circuit board (PCB). A picture of a typical 1D readout board is shown in Figure 3.3 and the individual strips can be seen in closeup on the right side of Figure 3.3.

The strips have a width of 80 µm and a pitch of 200 µm and are about 10 cm...
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Figure 3.3: The 1D readout board is shown on the left and a macroscopic picture of the strips is shown on the right.

A copper ground plane occupies the areas around the strips. This ground plane extends underneath the GEM in the detector which can be seen very well in Figure 3.3. The copper ground plane assures that the field lines from the cathode through the GEM will terminate under the GEM and stay parallel and straight all the way through the detector. The capacitance of the strips is measured to be $C_{\text{strip}} \approx 10pF$ per strip. The electronics board is attached at the end of the strips with a connector. The length of the wires from the connector to the Front End Electronics (FEE) board is kept as short as possible to minimize the extra capacitance introduced by the wires and therefore the noise.

3.2.2 2D readout board

The two dimensional readout board is manufactured by CERN’s printed circuit workshop and has strips going in the X and Y direction. The X strips are deposited on top of the Y strips and are electrically isolated from one another by a 50µm thick layer of Kapton. The top strips have a width of 50 µm and the bottom strips are
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wider at 150µm [43] to compensate for the loss in active area due to the top strips. A picture of the 2D board taken with a microscope is shown in Figure 3.4, which shows the size difference between the top and bottom strips.

Figure 3.4: Picture of the X and Y strips on the 2D readout board taken with a microscope.

The reason for the increased width of the bottom strips is to assure equal amount of charge sharing on both sets of strips. The CERN “Gas Detectors Development group” website [43] quotes that in this geometry the charge sharing is 50% larger on the top strips than on the bottom strips. The exact number for the charge sharing on the 2D board used in the detector is measured and the procedure to do this is described in Chapter 5.

The strip pitch on the 2D readout board is also 200µm. The size of the active readout region is 10cm by 10cm. Therefore, a total of 500 strips could be read out in each direction. In all the measurements taken with the 2D detector, sixteen strips in X and sixteen strips in Y were instrumented. A total of 96 strips in each direction
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could have been connected with the specific FEE board that was designed at BNL, but for the prototype stage the simpler configuration with 32 strips in total was chosen. For more details on the 2D readout board refer to [51].

3.3 Electronics

3.3.1 The Charge Sensitive Pre-Amplifier

The Preamplifier (PreAmp) used to readout the strips was developed by J. O’Connor’s group in the instrumentation division of Brookhaven National Lab (BNL) [52]. The chip comes in two versions: a sixteen channel version and an eight channel version. The eight channel version has lower noise with an equivalent noise charge (ENC) of $57 + 10/(\text{pF of input capacitance})$ and was used in the 2D detector setup. For the sixteen channel version the ENC is $88 + 15/\text{pF}$ and this version was used in the 1D setup. The size of the bare chip is very small at $2.2 \text{ mm by 6.12}$. The peaking time of the shaping amplifier on the chip is programmable to $0.6, 1.2, 2.4$ and $4.0\mu\text{s}$. It was set at $4.0\mu\text{s}$ for all of the measurements described in this Dissertation. The gain of the PreAmp is also programmable and the available settings are $30, 50, 100$ and $200\text{mV/fC}$. After investigating the noise and the size of the neutron events, the $50\text{mV/fC}$ gain setting was chosen. The lowest setting of $30\text{mV/fC}$ was not used because the noise recorded with this setting was below the 1ADC level of the digitizers and would have therefore not been recorded. Since the noise can give important information when looking at the data, it was decided to use the higher gain setting.

The PreAmp chips also have a test pulse input that allows for calibration of the digitizers. The input capacitor on the calibration input of the PreAmp chip has a capacitance of $C_{\text{test}} = 100f\text{F}$. How this test input is used to calibrate the detector is described in Section 5.2.
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The 8 channel, unpackaged version of the PreAmp chip was used on the 2D FEE board due to space constraints, whereas the 16 channel, packaged version of the chip was used on the 1D FEE board. The various inputs of the PreAmp, their function and where they are located on the PreAmp chip are shown in Figure D.1.

3.3.2 The Inverting electronics for the 1D and 2D detectors

An inverting circuit had to be used for both detectors since the Waveform Digitizers (WFD’s) that are used only permit signals of negative polarity as inputs. The direct outputs from the PreAmp chips only have positive polarity.

For the 1D board the inverters are mounted inside a box and are connected outside the vessel. A picture of the inverting electronics and how they are mounted inside the box is shown in Figure D.2 in Appendix D. The Operational Amplifier (OpAmp) used for this is the Texas Instruments OPA 2690 and the schematic of the inverting circuit is shown as part of the complete 1D setup in Figure D.8 in Appendix D. The 50Ω resistor on the output of the inverting circuit was added since the WFD has a 50Ω input impedance and the PreAmplifier alone can not drive it. The problem of driving 50Ω is another reason for using the inverting circuit.

For the 2D detector a different OpAmp was used in the inverting circuit, because they needed to be smaller in size and lower in noise. The OpAmps used for the 2D detector were the “ADA4851” OpAmp’s manufactured by Analog Devices. They are implemented in the same kind of circuit as the OPA2690. The inverting electronics for the 2D detector are located on the FEE board inside the vessel. A picture of the FEE board which includes the inverting circuit can be seen in the following section. The exact sizes of the resistors used in the inverting circuit for the 2D board can be found in Figure D.9 in Appendix D, which depicts the entire layout of the FEE board.
3.3.3 The 2D Front End Electronics board

The PreAmp chips and the 2D inverting electronics discussed above were mounted together onto one Front End Electronics (FEE) board for the 2D detector. This board was also developed in collaboration with J. O’Connor’s group in the Instrumentation division of BNL (mainly with G. DeGeronimo). The board holds the bare PreAmplifier chips, so that they could be directly connected to the readout board using wire bonds. This was done to keep the input capacitances to the PreAmp as low as possible to reduce the electronic noise of the PreAmps. A schematic of the electronic circuit of the entire FEE board is shown in Figure 3.5 and as a circuit diagram in Figure D.9.

![Schematic of the FEE board electronics.](image)

It can be seen in the schematic that the FEE board has a capacitor on the output line of the PreAmp. The reason for this is, that the PreAmp has an offset of the
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baseline of +300mV. This offset can be adjusted to zero by applying a voltage of -300mV to the baseline adjust (BA) input of the PreAmp (see Figure D.1). Since the baseline was needed to be at 0V, the 300mV offset was removed by capacitively coupling the output of the PreAmp to the inverting circuit, instead of adding another control line for the BA input. The FEE board also includes the inverting circuit and the 50Ω resistor for impedance matching with the WFD’s discussed earlier.

It can also be seen in the schematic in Figure 3.5, that a voltage regulator is added on the FEE board. It supplies the PreAmps with the needed +3.3V operational voltage. The voltage regulator used is the LT1764EFE-3.3 manufactured by Linear Technology. The regulator is low noise and adjusts input voltages from 3.8V to 20V to the 3.3V output. This regulator was chosen because it is low noise and due to its range, could also be used to output the \( \pm 5V \) needed to run the OpAmp in the inverting circuit. This allowed for using a single power supply to run both the PreAmps and the inverting electronics, therefore minimizing the noise introduced from the outside.

3.4 The Data Acquisition System (DAQ)

The Data Acquisition System consists of the components needed to read out the signals after they are taken out of the vessel. It consists of Waveform Digitizers (WFD’s), a customized LabView software and a VXI card that allows the computer to communicate with the WFDs. These components are described in detail below.

3.4.1 The Waveform Digitizer (WFD)

The Waveform Digitizers are on loan from Ed Kerns from Boston University. They were originally designed for the MACRO experiment and have since been loaned out
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to various other experiments. The WFDs have a flow through design, which means the analog waveform from an event in the detector comes into the front panel, is then modified by front-end amplifier circuits, is then converted to digital data by a flash analog to digital converter (FADC) and then stored in RAM (random access memory). The RAM is readout through the VME backplane by the computer, which is described in the following section.

The important features of the digitizers are as follows: The digitizers have a clocking rate of 200MHZ, resulting in a time resolution of 5ns; the memory buffer has 64kB/channel of memory, allowing for a waveform of $163.835\mu\text{s} (32\text{kB})$ length to be stored per event; the buffer is a ring buffer and rolls over to the beginning when its end is reached; the second set of 32kB/channel memory buffer is used to store discriminator threshold information and time information; a control storage area for each channel allows for the setting of the discriminator thresholds, resetting of the WFDs and various other functions; the maximum input into the digitizers is 2.5V before they saturate. Each WFD board has 16 inputs, but multiplexing for the input channels is implemented. This means that every input channel is made up of four separate inputs. Each group of four channels is summed before being written to the buffer. If using more than one input for each channel, each individual signal is discriminated and 4 bits are associated with each sample to identify which channels contributed to that time slice of the waveform. The multiplexing feature of the WFDs was not used in any of the measurements described in this Dissertation, since a maximum of 32 channels were needed and 8 digitizers were on hand.

For operation of the WFDs, every WFD board needs a 200MHz, sinusoidal clock input as well. This signal is generated using a WaveTek 0.01-1100MHz synthesized signal generator model 2410, which is send through a custom Fanout to every WFD board. A START and STOP signal needs to be provided to each WFD as well, which needs to be a NIM standard square pulse. The STOP signal is provided from the
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hardware trigger (see Section 3.5). The START signal is created by the computer after the readout of the WFD buffer is finished. It is created through a National Instruments Digital I/O unit (BNC-2090). Both, the START and the STOP signal, are send through a Logic Fan-Out unit (LeCroy Model 429A) to each WFD.

3.4.2 LabView software

The data is acquired from the WFD’s through the computer using a custom LabView program created to readout the WFD’s after a trigger happens. A diagram depicting the different steps in the LabView software is shown in Figure D.3.

When a trigger happens (a waveform crosses a preset threshold in the discriminator unit as described in Section 3.5), a designated digital input line on the National Instruments digital I/O unit (NI I/O unit) turns to high and the LabView program knows that the WFD’s are stopped and can be read out. The data is then read out from the WFD buffer using a VME-VXI card to interface the computer with the VME backplane of the WFD crate. Then the program checks that at least one of the signals is higher than a preset noise threshold (set on the front panel of the LabView software by the user). After this, the program calculates the area under all the waveforms in the data that are greater than the preset noise threshold (from zero crossing to zero crossing). The units of the areas are in summed ADC (SADC) counts. The sums of these areas are then histogrammed and plotted on the front panel for each event. This is done to allow the operator to monitor the data taking. All the individual waveforms are also plotted after each event in one designated plot.

All the waveforms of a single event are then stored as a “.dat” file. The datafile has a header that contains the time and date of the run, the voltage across the GEM and the electric field in the drift region. Each event has 32767 rows of data ($\approx$163$\mu$s) and stores each input channel in a separate column (number of columns is equal to
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the number of input channels). After each event a row of (-1)'s is added to mark the end of an event unambiguously, and this simplifies the analysis of the data later on. The reason entire waveforms of lengths of up to 163$\mu$s are stored is that this way all the information of each input channel is stored and is available for analysis.

3.5 The Trigger

Two different triggers were used in every data taking run. The hardware trigger would stop the WFD’s and prompt the LabView to read out the buffer of the WFDs. The trigger set in the LabView software was used to only write events to file that were big enough to meet certain criteria. The software trigger was added since it allowed for finer control of the pulseheight threshold required for an event to be saved.

3.5.1 The hardware trigger

The hardware trigger used for the 1D board and the neutron generator runs with the 2D board was different from the trigger used starting in January 2008. The schematics for both hardware trigger schemes are shown in Figures D.4 and D.5. For the former situation, the sum of four channels was put into a discriminator unit (Ortec model 436, 100MHz discriminator, negative output used) with variable threshold, which would create the trigger signal. Optimally one would like to trigger on the sum of all channels, that would trigger readout of the WFDs even when only one strip has a non zero signal on them. At the time of the first data runs, only two summer units were available and since they were also inverter units, only four channels could be used in the trigger. The summers used were an ORTEC dual summer/inverter unit, model 533 and a Tennelec dual summer/inverter unit, model
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TC212. Triggering on only 4 channels simultaneously allowed for triggering on tracks of length $\geq 600\mu m$. To put the four signals that are giving the trigger signal into the summer, the input was split at the WFD level with a T connector, one line going into the WFD input and the other going into one of the summer units (the TC212). The input impedance of the Tennelec summer unit is $5k\Omega$, so the signal will be attenuated by about 2% at the WFD level. This is taken into account in the analysis of the data.

From the first summer, each summed signal is send to the second summer/inverter unit (Ortec), in order to preserve the negative polarity of the signal and to sum all 4 channels together. The output of the Ortec summer/inverter unit is then send to the discriminator unit (Ortec 436). To provide the software and the WFD with a STOP signal, the output of the discriminator is sent to a logic unit (LRS 365AL) where the signal is split into two. The first output of the logic unit is sent through a delay generator (ORTEC model 416A), to a TTL to NIM level adaptor (Lecroy model 688AL) and through the previously mentioned Fanout unit (Lecroy Model 429A) to the WFD STOP input. This will stop the WFDs. The delay generator is needed to delay the stop signal enough to allow the WFD to record the entire signal in its buffer before readout is initiated. Adjusting the delay time allows for positioning of the signal in the middle of the buffer, so any signal before or after or any interesting structure of the signal will also be recorded in the buffer. The second output from the logic unit is sent to a Dual Gate Generator (LRS model 222) and the TTL signal output is then send to the NI I/O unit to create the STOP signal for the computer.

After the first 2D run with the DD neutron generator, the trigger scheme was improved over this initial setup. A summer was built with 16 inputs that are AC coupled (to not attenuate the signal at the WFD level) and either sums only 8 channels together to give two separate summed outputs, or it sums all 16 input channels together to give one summed output. It also allows for two different gain settings. The low gain is equal to one and the output is equal to the sum of the input channels. The high gain is set at a factor of two, so the output is equal to
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the sum of the inputs times two. The high gain is used when the noise of the input channels is so low that it needs to be increased in order to allow the discriminator to trigger on the noise. The discriminator’s lowest setting is at 60mV and the noise of the channels is about 6mV for the lowest gain setting on the Pre-Amplifiers. The novel summer uses the OPA2690 and OPA2132 and a schematic of the circuit can be found in Figure D.7. A picture of the front panel of the new summer unit is shown in Figure 3.6 and a picture of the inside of the NIM module is shown in Figure D.6.

Figure 3.6: The front panel of the new summer unit used from January 2008 onwards.

The output of the summer unit is also sent to the same discriminator unit described above for the old trigger. The rest of the trigger scheme is therefore the same as described above for the old trigger. A picture of all the modules used in the hardware trigger setup can be seen below in Figure 3.7.
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Figure 3.7: All the NIM modules used to create the START and STOP signals for the hardware trigger. Both summer units used are shown.

3.5.2 The software trigger in the LabView program

After triggering and stopping the WFDs with the hardware trigger, different triggers in the LabView software can be set such as not to write an event to file if these criteria are fulfilled. One of these triggers is a noise threshold in ADC counts which can be set in the LabView front panel. If none of the pulseheights of each strip recorded is larger than this threshold, the data is not written to file. Another setting that can be chosen in the LabView front panel is called the “coincidence threshold”. If only contained events (events that have no or small charge on strips 1x and/or 16x) are supposed to be written to file, this threshold, in ADC counts, can be set to a small number. Now, if the outside strips - for example 1x and 16x are connected to the coincidence channel (always the last WFD channel to be read)- have a charge
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greater than the coincidence threshold, the event will also not be written to file and the other WFD channels are not read either. This setting is only implemented when running $^{55}\text{Fe}$ calibrations as discussed in Section 5.1.

3.6 The complete 1D detector setup

After introducing all the components of the detector above, the complete setup will be described here. The one dimensional readout board is mounted on top of a labjack (to adjust the distance of the GEM to the cathode, therefore changing the drift volume) and the GEM is mounted on top of the readout board using nylon screws and washers. The distance from the GEM to the readout board is kept constant at 2.55mm. It is very important to know this number well since the electric field across this gap is very high and needs to be chosen in a way that the field in the region is far away from breakdown, as any spark from the GEM to the readout board could potentially destroy the board and/or the front end electronics. A picture of this setup is shown in Figure 3.8.

The cathode is mounted on top a Lexan structure that the lab jack was mounted into. The cathode was about 12cm by 12cm in size and made out of copper. The thickness of the copper was not important, so a thickness of 2mm was used to assure that the cathode would not bend in the electric field and therefore bend the electric field lines in the drift volume.

The strips from the readout board are then connected to the 1D FEE board using a connector as described before. A picture of the 1D detector inside the vessel with the FEE board connected is shown in Figure 3.9.

The outputs from the PreAmp are then sent through the inverting circuit to the WFDs. This setup is schematically shown in Figure(D.8).
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Figure 3.8: The 1D detector setup is shown here. It can be seen how the GEM is mounted on top of the readout board and how this sits on top of the labjack. The cathode has been removed for these pictures, but it is indicated where it would be mounted.

Figure 3.9: The 1D detector inside the vessel. The way the FEE board is connected is also shown and how the output channels are connecting to the feedthrough.
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3.7 The complete 2D detector setup

A schematic of the detector setup can be found in Appendix D, Figure D.9. The FEE board was directly attached to the 2D readout board using regular glue and nylon screws (in case the CS$_2$ would dissolve or attack the glue). As mentioned before the PreAmp chips were directly wirebound to the readout strips on the board. Due to the size of the PreAmp chip, it was not possible to connect 8 adjacent channels to it. To solve this problem, a FEE board was mounted on each side of the readout board and then the strips were connected in an alternating fashion. This is depicted in the sketch in Figure 3.10. Therefore, one PreAmp chip would read out the even numbered strips and the one on the opposite side would read out the odd numbered strips. This is true for both sets of strips, X and Y.

![Figure 3.10: How the PreAmp chips connect to the even and odd strips in an interleaving fashion is shown here. This configuration is used for the X strips as well as the Y strips.](image)

The GEM, in this case a 7cm x 7cm copper GEM manufactured by CERN, was mounted on top of the readout board using a custom made acrylic frame. The frame has a thickness of 1.58mm. With the GEM frame thickness of 0.9mm, this sets the distance from the bottom of the GEM to the readout board at a fixed value of about 2.48mm. The GEM was glued onto the frame and the frame with the GEM was
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disposed of if the GEM broke during operation. The frame and the GEM were then attached to the readout board using nylon screws.

Figure 3.11: The complete 2D detector setup with the cathode mounted over of the readout board. The GEM on top of the readout board and parts of the FEE boards can be seen as well.

For the 2D detector a new cathode was cut from a 2mm thick sheet of copper, which was sized to fit over the smaller GEM surface to avoid unknown electric field lines on the outside region of the detector. The size of the cathode is 8cm x 8cm. The cathode was also mounted on an acrylic frame and mounted on top of the nylon screws that held the GEM in place. The spacing between the cathode and the top surface of the GEM was chosen to be 2cm and was held at that value using spacers and washers of known thickness. This setup is shown in Figure 3.11. The detector would then sit inside the vacuum vessel on top of a grounded lab jack which is shown in Figure 3.12.

For all the data taking runs, the GEM was powered by a Keithley High Voltage
Chapter 3. Detector Setup

Figure 3.12: The complete 2D detector setup inside the vessel is shown here. All the connectors for the signal channels, programming and voltage inputs can be seen as well. The pieces of lead seen on top the cathode are used to collimate and shield from the $^{55}\text{Fe}$ source.

Power Supply (Keithley model 248), which has a maximum output of 5kV. The cathode is connected to an Ortec High Voltage power supply (Ortec model 456, 3kV maximum output). The way the GEM is connected to the power supply is through a resistor chain that steps down the voltages to the desired $\Delta V_{GEM}$. This is depicted in Figure 3.13. The values of the resistors in the picture are the ones used for all the runs in CS$_2$ (40, 80 and 120torr). The distances from the cathode to the GEM and the GEM to the readout board are $d_{CG}=2\text{cm}$ and $d_{GR}=2.54\text{mm}$ respectively.

The PreAmp output signals were connected to custom 85 pin feedthroughs using twisted pair ribbon cable. Each pair of wires in the ribbon cable would always carry one signal wire and the other would be a ground wire. The connector used for programming the PreAmp was also connected with these cables but was taken out of
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Figure 3.13: Setup for the 2D detector that shows how the cathode and the GEM are supplied with voltage.

the vessel using a different feedthrough to avoid any kind of crosstalk between signal and programming wires. The programming feedthrough was also used to supply the voltage regulator on the FEE board with its needed ±5V and GND connections. For this a simple ribbon cable was used, alternating GND connections with the ±5V connection.

On the outside of the vessel, the signal cables are attached to a box that converts the ribbon cable to LEMO connectors. This box can be seen on the left in Figure 3.14.

From here they were then connected to the WFDs using 12ft long LEMO cables. The program wires and the ±5V wires were fed into a different box, shown in the right side of Figure 3.14. This box would connect the programming channels to dip switches that would allow the user to program the PreAmp accordingly. These boxes also incorporated inputs for the ±5V needed to run the PreAmp and OpAmps inside the vessel and included a voltage regulator. A schematic of the box can be found
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Figure 3.14: The box that converts the ribbon connector to LEMO connectors on the outside of the vessel is shown on the left. From here the LEMO cables connect to the WFDs. The picture on the right shows the box that is used to program the PreAmps and supply the electronic components inside the vessel with power.

in Figure D.10. Figure 3.15 shows a picture of the two boxes containing the signal wires and the programming functions outside of the vessel.

Figure 3.15: Two of the boxes that convert the signal from ribbon cables to LEMO cables (on the right) and that contain the programming for the PreAmp chips (on the left) and how they connect outside the vessel is shown in this picture. The feedthroughs and ribbon cables used can be seen.
Chapter 4

Data Analysis

The analysis procedure is divided into three parts; a primary analysis, secondary analysis and a final analysis. The primary analysis is performed on all files and converts the data file into a format usable by the ROOT data analysis package developed at CERN [53]. It identifies pulses in an event and stores important information pertaining to them. In the secondary stage of the analysis, tracks are formed from the previously found pulses and run specific cuts are introduced. Various quantities important to a “track” are defined in this step as well. The final analysis combines various runs together and can be used to extract any desired information. The final analysis is specific to a certain run type, for example it would be different for a neutron run than an $\alpha$ run and is used to combine only the important information for a certain analysis goal.

4.1 Primary analysis “readdat”

All the analysis code used in this Dissertation uses ROOT interpreted C++ code as well as compiled C programs. The first step in the analysis is to read in the raw data
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file and convert it into a .root file. This is done by the program called “readdat”.

The input files have the syntax timedateyear_runtype-direction_runnumber_2D(or 1D)_v1.dat and the output file has the extension “.dat” removed and replaced with “-wfd.root”. For example “092505022008_Po210-x16_0_2D_v1.dat” (run performed at 09:25am on the 2nd of May 2008, with the Polonium 210 source from the X16 side with the 2D detector) becomes “092505022008_Po210-x16_0_2D_v1-wfd.root”.

The various run types are “252-Cf” (Californium source neutron run), “DD” (DD gun neutron run), “55Fe” (\(^{55}\)Fe calibration run), “calibration” (test pulse input calibration), “background” (runs with no sources at low trigger threshold), “Po210” (\(\alpha\) particle calibration) and “60Co” (\(\gamma\) calibration). The different directions are “x1” (from strip 1X side), “x16” (from strip 16X side), “y” (from strip 1Y or 16Y side), “zup” (from below the detector) and “zdown” (from on top of the detector). For some files the direction is not important and no extension is inserted in that case (for example for the \(^{210}\)Po run).

A typical event shown in the event display can be seen in Figure 4.1. The event display is used to check events and make sure collected events are not “irregular” in any way. The particular example of an event display in Figure 4.1 is taken from a \(^{210}\)Po run, which is why there is a large signal on the Y strips and no visible signal on the X strips (pulses are very small on X). All the available channels are plotted in the event display, 1X is set at zero ADC counts and the subsequent channels are staggered at a certain offset above it. The offset is chosen as the ADC value of the largest pulse in the event. This is the reason small pulses can not be seen in Figure 4.1, since the very large pulses on the Y strips determine the scale of the display. The X axis in this plot is in units of time, where one time bin corresponds to 5ns. It is important to remember, that the waveforms are purely positive. If negative components of the waveform exist, they are seen as zeros in the data record. This is due to the WFD’s and has been described in Section 3.4.1.
Figure 4.1: A sample event displayed in the event display. All strips are plotted with an ADC offset. The lower 16 strips are the X strips and the top strips are the Y strips as labeled. The x axis displays time, where one time step corresponds to 5ns.

Prior to any kind of analysis, every waveform on each channel is smoothed using triangular smoothing with 100 bins. The reason to smooth the data is due to the high digitization rate relative to the length of a pulse. Since the shaping time used is $4\mu s$ and the digitization rate is 200MHz, the ADC value is stored every 5ns. This means that when zooming in on a pulse, an area in time that would correspond to a set ADC value will oscillate around that value by one ADC count. This can be seen in Figure 4.2.

In this particular example the first zero crossing can be defined as being at about 9800 time bins, or when looking more carefully at 9500 time bins. This corresponds to a discrepancy of $1.5\mu s$ and would lead to a large error on the width of a pulse in time. When smoothing the pulse, the exact time of the zero crossings or the
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Figure 4.2: A sample pulse from a $^{252}$Cf run on one of the X channels. On the left is the pulse and on the right is a smaller time slice of the pulse. It can be seen here, that it will be hard to define the first zero crossing of the pulse since the ADC value oscillates wildly from 0 to 1 beginning and end of the pulse can be determined much more easily. A smoothed pulse can be seen in Figure 4.3.

For the triangular smoothing, the ADC value of each point in time is determined via

$$ADC_j = \frac{\sum_{i=j-nbin/2}^{j+nbin/2} ADC_i}{\sum_{k=j-nbin/2}^{j+nbin/2} (nbin + 1 + k) \sum_{l=j+1}^{j+nbin} (nbin + 1 - l)}$$  \hspace{1cm} (4.1)

In this expression, $nbin$ is the number of bins used for the triangular smoothing, which, as mentioned before, is chosen to be $nbin=100$ throughout this work. $ADC_i$ is the ADC value of the $i$-th time bin. An example of a smoothed waveform in comparison with the unsmoothed waveform is seen in Figure 4.3. It can be seen well in Figure 4.3 that in the case of the smoothed pulse, many variables of the pulse will be described better. Which these are is discussed in detail in the following.
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Figure 4.3: A sample pulse from a $^{252}$Cf run on one of the X channels. On the left is the original pulse and on the right is the pulse when smoothed using triangular smoothing with 100 bins.

4.1.1 Pulses

After smoothing the data, the next step in the analysis is to find the pulses. This is done separately on every channel. To visualize the pulse finding procedure, a sample pulse, shown in Figure 4.4, defines the different variables of each pulse.

The pulse is found by the analysis program $TFEvent.cc$ by looking for the maximum ADC on the data record for a particular channel. This maximum is associated with the peak time “peakt” of the pulse. Once the maximum is found, a loop is run that steps backwards in time from $peakt$ to the start of the pulse “start”. The start of the pulse is defined as the time bin of the data record where the corresponding ADC value is less than or equal to the threshold value defined below. The other loop will go forward in time until it finds the end time bin “end” of the pulse the same way. Once the first pulse is found on one channel, the program will look before this pulse in time and after this pulse in time to find a maximum of three pulses on each channel. The reason to allow for a maximum of three pulses on each channel is, that by browsing through events, it became clear that a very small number of events will
Figure 4.4: A sample pulse from a $^{252}$Cf run on one of the X channels. How the start time, peak time, end time and area under the pulse are defined is shown here. Also the threshold that defines the start and end times is shown here. It is given as $\mu + 3\sigma$ of the noise on that particular channel.

actually contain more than one pulse. What is done with the multiple pulses on one strip is described in Section 4.2.1.

The pulse threshold used to define the start and end time bins of a pulse is defined as:

$$ threshold_i = \mu_{\text{noise}(i)} + 3\sigma_{\text{noise}(i)} $$  \hfill (4.2)

In this expression, $\mu_{\text{noise}(i)}$ and $\sigma_{\text{noise}(i)}$ are the mean and the spread of the noise
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on the i-th channel. For every channel all the ADC values outside of a pulse are added together. Then this sum of ADC values is divided by the number of time bins evaluated to create this sum. This average noise of the i-th channel is then histogrammed for all the pulses in one particular data run. An example of such a noise histogram for one particular channel is shown in Figure 4.5.

Figure 4.5: Histogram of the average noise on one channel for a neutron run. The width and spread of the noise in this particular case would be $\mu_{\text{noise}(i)} = 0.001$ and $\sigma_{\text{noise}(i)} = 0.052$.

A Gaussian is then fit to the noise histogram and the mean ($\mu$) and standard deviation ($\sigma$) recorded. This is done separately for all channels and compared across various runs to ensure stability of the noise. The specific values of the mean and the sigma of each channel can be found in Table D.3 of Appendix D.

To summarize the discussion of the “pulses”, the following characteristics of the
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pulse are calculated and stored in the “sevent” (for smoothed pulses) branch and the “event” branch (for unsmoothed pulses) of the root tree:

- “strip”: Strip number of the channel the pulse is found on (0 to 15 correspond to 1X to 16X and 16 to 27 contain the Y strips grouped together as defined in the event display in Figure 4.1)

- “start”: Starting time bin of the pulse. Found as the first time bin of a pulse before the peak time that has an ADC value below threshold.

- “end”: End time bin of the pulse. Found as the first time bin after the peak time that has an ADC value below threshold.

- “length”: Length of the pulse in time bins. Defined as the difference between the end time bin of the pulse and the start time bin.

- “sum”: Area under a pulse, calculated by summing all ADC values of the time bins from “start” to “end”.

- “peakt”: Time bin at which the maximum ADC value of the data record for a specific channel is found.

- “peak”: Pulse height in ADC counts of the peak of a pulse.

- “thalf”: Time bin at which the area of a pulse before “thalf” is equal to the area in the pulse after “thalf”.

In the TFEVENT class, the Sumline is also introduced. The Sumline is created by summing all X strips together, defined as

\[ SADC[i] = \sum_{j=0}^{j=X\text{STRIPS}} ADC[j][i] \]  \hspace{1cm} (4.3)
This sums the $i$-th ADC value of each strip and stores it in the *Sumline* $SADC[i]$. Various variables are defined for a pulse on the *Sumline*, just as they were for the regular pulses. A pulse on the *Sumline* is found the same way described for individual pulses. The variables defined for a pulse on the *Sumline* are

- “$S_{\text{start}}$”: Starting time bin of the Sumpulse. Found as the first time bin of a pulse before the peak time that has an ADC value below threshold. For the Sumline the threshold is chosen as 2ADC
- “$S_{\text{end}}$”: End time bin of the Sumpulse. Found as the first time bin after the peak time that has an ADC value below 5ADC.
- “$S_{\text{length}}$”: Length of the pulse in time bins. Defined as $S_{\text{end}} - S_{\text{start}}$.
- “$S_{\text{halftime}}$”: Time that is half the length of the pulse, defined as $S_{\text{start}} + S_{\text{length}}/2$
- “$S_{\text{qleft}}$”: Sum under the Sumpulse from $S_{\text{start}}$ to $S_{\text{halftime}}$.
- “$S_{\text{qright}}$”: Sum under the Sumpulse from $S_{\text{halftime}}$ to $S_{\text{end}}$.

### 4.1.2 Events

An “event” is constructed from the pulses that are found with the pulse finder algorithm described in the previous section. Any pulse whose length is less than 50 time bins (or 250ns) is disregarded and not saved as a pulse in the event. The reason to chose 50 is, that noise, that is found to be oscillating around 1ADC count, will be disregarded this way. Noise fluctuations usually have a length of five to ten time bins. It is also checked that the maximum pulse height of a pulse is greater than the pulse threshold described above. If it is less than the threshold, the pulse is also removed. This is a precaution as the 50 time bin cut should remove these pulses.
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The characteristic variables saved for an event are:

- **“nev”**: Number of the event.
- **“qtot”**: Total charge in the event, calculated by adding “pulse→sum” for all pulses in the event.
- **“np”**: Number of pulses in a given event.

The information for the events is also stored in the “event” and “sevent” branch for the smoothed and the unsmoothed data in the ROOT tree. This allows for a direct, pulse by pulse comparison of the smoothed and unsmoothed pulses and therefore ensures that the smoothed data behaves the same as the original data does and no information is distorted or lost by the smoothing procedure.

4.2 Secondary analysis “ana”

In the analysis code _ana.c_, the -wfd.root file created by _readdat.c_ is read. The output file name is created by removing the “-wfd.root” from the input filename and replacing it with “-ana.root”. For example “092505022008_Po210-x16.0_2D_v1-wfd.root” becomes “092505022008_Po210-x16.0_2D_v1-ana.root”.

In this step of the analysis, only the variables created from the smoothed data are used (after it has been assured that the smoothed data gives the same or better results then the unsmoothed data). For this step of the analysis various conversion constants are used to convert the variables in the data to physical variables. The different constants needed are:

- **“toNIPs”**: Constant that is used to convert the area under a pulse from SADC counts to NIPs. This constant is calculated from the $^{55}$Fe calibration
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discussed in Section 5.1.

• “driftv”: Drift velocity of the negative ions in \( CS_2 \). This value is different for different pressures of the gas and in different electric fields. Since all data is taken at drift fields of \( E_D \) 750V/cm, the values used are \( driftv_{40\text{torr}} = 74 \frac{m}{s} \), \( driftv_{80\text{torr}} = 37 \frac{m}{s} \) and \( driftv_{120\text{torr}} = 25 \frac{m}{s} \). How these drift velocities were found is discussed in Section 6.2.

• “tToDist”: Constant used to convert time bins to distance in mm. This constant is calculated as \( tToDist = driftv \cdot 5.0 \cdot 10^{-6} \). The \( 5 \cdot 10^{-6} \) is due to the fact that every time bin in the data record corresponds to 5ns. When a time is converted from time bins to time in \( \mu s \), it is multiplied by \( 5 \cdot 10^{-3} \). The extra factor comes from converting the time to distance in mm.

How these constants are used in the analysis will become clear in the following section and is discussed for each of the constants separately.

4.2.1 Tracks

Tracks are defined differently from events since they will only allow for one pulse per strip to be part of a track and define many more variables that are inherent to a track, not just a single pulse, for example the extent of a track in X. If there is more then one pulse on a given channel, only the largest one will be included in the track. This is a valid assumption, since the only reason there are two pulses on a given channel is that there might be some noise before or after a pulse that looks like a pulse. This will always be smaller then the main pulse though and can be disregarded.

An example of an event (only a few X strips are shown for simplification) is shown in Figure 4.6.
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Figure 4.6: Sample event from a $^{252}\text{Cf}$ run visualizing the definitions of $q_{left}$, $q_{right}$ and $asym$.

The important variables to a track are:

- **“npulses”**: Number of pulses in a track. Different from “event $\rightarrow$ np”, since only one pulse per strip is counted.

- **“qnips, qnipsx, qnipsy”**: Total event charge in NIPs (qnips) of the total event calculated as $\sum_{pulses} q[i]$ ($q[i]$ is defined below). qnipsx (qnipsy) is the event charge in NIPs on the X (Y) strips calculated as $\sum_{X(Y)\text{pulses}} q[i]$. The total charge in NIPs can also be calculated as $qnips = qnipsx + qnipsy$

- **“$q[i]$”**: Charge in NIPs on the i-th strip. It is found as the charge of the pulse on the i-th strip “pulse $\rightarrow$ sum” multiplied by the constant $toNIPs$
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- “xstrips”: Number of strips in X that have a charge of \( q_i \) \( \geq 10NIPs \) on them.

- “x”: Extent of a track in X. This is calculated by multiplying the number of strips hit, “xstrips” in X by 0.2mm (strip pitch).

- “Dz”: Extent of a track in the z direction. This is calculated from the length of a track in time bins multiplied by the constant \( tToDist \). The length of a track in time bins is found by taking “pulse \( \to \) thalf” of each pulse in the track and then taking the difference between thalf of the first pulse (in time) of the track and the last pulse (in time) of the track. This difference defines the extent of the track in time bins.

- “Dy”: Extent of a track in Y, calculated by multiplying the number of strips hit in Y by 0.2mm (strip pitch).

- “R3 (R2)”: 3 dimensional range of the track, calculated as \( R3 = \sqrt{x^2 + Dz^2 + Dy^2} \). If no information in Y is available, a two dimensional range in the X-Z plane can be calculated as \( R2 = \sqrt{x^2 + Dz^2} \).

- “qleft” (“qright”): When a track is recorded, the strip in the middle of the track on X is found middlestrip. qleft (qright) is the sum of the charge that is on the strips before (after) the middle strip. If the number of strips hit in an event is even, the charge on the middle strip is not used. To visualize this definition, a sample event with the definitions is shown in Figure(4.6). qleft and qright are used to calculate the head-tail asymmetry \( asym \) of a track.

- “asym”: Asymmetry in the charge on the X strips, calculated as \( asym = \frac{qright-qleft}{qright+qleft} \). This will be used to investigate the existence of the head-tail effect in the neutron data.
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- **“ZasymC”**: Asymmetry in the charge in the Z direction, calculated as \( Z_{asymC} = \frac{S_{right} - S_{left}}{S_{right} + S_{left}} \). This will be used to investigate the existence of the head-tail effect in the Z direction.

- **“avwi”**: Average width of the pulses in a track calculated by adding the width of all pulses in a track and dividing by the number of pulses in an event.

All the track variables are stored in the \textit{tracks} branch of the new ROOT tree.

After the track finding is complete, certain cuts are introduced to store the tracks that are relevant to the current run. These cuts are very run specific though, very different cuts are employed when looking at for example \( \alpha \) runs compared to \( ^{252}\text{Cf} \) runs. For this reason, they are discussed separately in the different sections describing the various runs.

4.2.2 Removing bad tracks

Certain tracks are removed from the data due to certain characteristics. These events are cut run-independently in the \textit{ana.c} analysis stage. The tracks cut are as follows

- **Tracks that run off the buffer**: Some of the tracks have an extent too large in the Z direction that they will run off the digitizer buffer and can therefore not be used in the final analysis. A sample event that runs off the buffer is shown in Figure 4.7. It can be seen how the event runs off the buffer since some of the pulses are cut off when they reach the end of the data record.

- **Noise events**: These are certain tracks that are narrower in time then regular events, are completely straight in Z and appear on each of the strips, including all X and all Y strips. An example of such a track is shown in Figure 4.8. These events are either due to noise or could be events created in the transfer region.
between the GEM and the readout board. Either way, they are also removed from the data.

Figure 4.7: Sample event from a $^{252}$Cf run visualizing a track that runs off the buffer due to its large extent in the Z direction. The pulses on strips 4 and 5 are incomplete since they run off the data record.

### 4.3 Final Analysis

The final analysis is done separately from the initial analysis and does not create .root files as output. All the final analysis is used to combine various data files of a certain run into one large run. For example, due to LabView restrictions, one X directed $^{252}$Cf run might be split up into four of five different data files. To analyze all the data together though, these files need to be combined, which is done in the final
Figure 4.8: Sample event from a $^{252}$Cf run that was cut since it is narrow in time and shows hits on all X and Y strips.

analysis. If anything particular is done in such a final analysis besides combining data files, it is mentioned in the specific section.
Chapter 5

Detector calibration

Before taking data with a neutron source to measure low energy nuclear recoils in the detector, the detector needs to be calibrated. Various calibrations need to be performed to know: the energy scale of the events; the gas gain of the detector; the charge sharing of the X and Y strips on the 2D readout board; the gain of the readout electronics and the strip to strip gain uniformity. All of these calibrations can be performed using different radioactive calibration sources. These techniques are described in the following chapter.

5.1 Energy calibration with $^{55}$Fe source

An $^{55}$Fe source is used to calibrate the energy scale of the detector, the gas gain and the charge sharing of the X and Y strips. To ensure gas gain stability during data taking runs, periodic exposures of the detector to the $^{55}$Fe source during runs are taken.

$^{55}$Fe is a radioactive isotope whose dominant decay produces x-rays of energy $E_{\text{x-ray}} = 5.895$keV. This x-ray will interact mainly with the Sulfur atoms in the CS$_2$
gas, because the mean free path for the x-ray interacting with the Carbon atom is very large (540 cm) and there are twice as many Sulfur atoms.

When the x-ray interacts in the gas, it will be absorbed by a Sulphur atom in the K shell through the photoelectric effect, resulting in the emission of a photo electron. The energy of the photo electron is determined through the difference of the energy of the incoming x-ray (5.895 keV) and the energy needed to remove the electron from the K shell (for S it is 2.472 keV). The atom is now in an excited state and can de-excite via two different processes. The first possibility is de-excitation through the Auger effect, where electrons in the L shells reconfigure which results in the emission of an electron. No energy is lost if de-excitation happens through this channel, so the total energy deposited in the detector volume is equal to the original 5.9 keV energy of the x-ray. This peak in the spectrum is also referred to as the "main peak" (MP) of the spectrum, since this channel of de-excitation is more likely (92.4% probability). The second channel for de-exciting the atom is through fluorescence. Here, an electron from the L shell will drop down to the K shell, in the process emitting a photon of energy $E_\gamma = E_K - E_L = 2.241$ keV. The probability this will occur is 7.6% for a S atom.

Since the Auger effect is more likely to occur the main energy in the spectrum will be the 5.9 keV of the incident x-ray. This can be prominently seen in the spectrum shown in Figure 5.1. This spectrum was created with the $^{55}$Fe source using the 1D detector in 80 torr CS$_2$.

The main peak appears in this example at about $\text{SADC}_{MP}=8.75 \cdot 10^5 \text{SADC}$ counts and can be used to energy calibrate the detector. In CS$_2$ the ionization potential $W$ is energy dependent, but for the 5.9 keV x-ray it is approximately $W=19$ eV. The x-ray therefore creates a fixed number of free electrons in the gas, which is $N_e=300 \pm 40$ e$^-$ in 40 torr CS$_2$ [54]. These electrons quickly attach to the electronegative CS$_2$ molecules and the now negatively charged ions are drifted and readout in.
Chapter 5. Detector calibration

Figure 5.1: Example of an $^{55}$Fe spectrum obtained in 80 torr CS$_2$ with $E_D = 680$ V/cm, $\Delta V_{GEM} = 474$V, $E_i = 4200$ V/cm.

the previously described fashion.

A second, smaller peak can also be seen in this spectrum (at about $5\cdot10^5$SADC). This is the escape peak (EP) of the $^{55}$Fe spectrum, which occurs at an energy of about $E_{EP} \approx 3.4$keV. This peak is created in the spectrum, when the previously described fluorescence photon does not interact in the active detector volume (its mean free path is $\approx 21$cm in CS$_2$) and is therefore not detected. The only energy seen then is from the initially created photo electron, which had an energy of 3.4keV). Since the fluorescence only happens 7.6% of the time, the height of the escape peak relative to the main peak is greatly diminished. It is also worth mentioning that, since the escape peak is at smaller energy then the main peak, the escape peak can be lost in the noise if the gas gain is not sufficiently high to resolve it. Therefore, most $^{55}$Fe spectra shown for the neutron data will not show this beautifully resolved escape
Chapter 5. Detector calibration

peak as in the figure above.

During an $^{55}$Fe exposure of the detector, the trigger channels are only the X strips. It is triggered directly on the $^{55}$Fe pulses. A sample event from the main peak is shown in Figure 5.2. In this example, the lower 6 strips are hit, which is typical for a main peak event. It is also interesting to note that the pulses have a lot of structure to them; they are not simply Gaussian waveforms. A sample event from the escape peak is shown in Figure 5.3. Only 3 strips are hit in this event, which is due to the smaller energy deposition due to the escaping $\gamma$.

To calibrate the energy scale of the detector, the main peak position in SADC counts is related to the 300NIPs of primary ionization through a conversion factor.

Figure 5.2: Example of an $^{55}$Fe main peak event in 80 torr CS$_2$ taken with the 1D detector setup on 16 X channels.
Chapter 5. Detector calibration

Figure 5.3: Example of an $^{55}$Fe escape peak event in 80 torr CS$_2$, taken with the 1D detector setup on 16 X channels.

$C_{NIPs}$ as follows:

$$C_{NIPs} = \frac{Q_{MP}}{SADC_{MP}}$$  \hspace{1cm} (5.1)

For the $^{55}$Fe spectrum shown in Figure 5.1, the conversion factor is given as $C_{NIPs} = \frac{300NIPs}{8.75 \cdot 10^3 ADC} = 3.429 \cdot 10^{-4} \text{ NIPs/SADC}$. Using this number, calculated for each calibration run taken immediately before a neutron run, SADC’s can now be converted to NIPs in the neutron data.

To know how good the energy resolution of a given run is, the width of the main peak is measured. It varies by a maximum of about 10 to 15% from run to run. It is larger when the GEM gain is low and smaller when running at high GEM gains. In the case of the sample spectrum in Figure 5.1, it is given as $\sigma_{MP} = 0.670 \cdot 10^5 \text{SADC}$,
resulting in an energy resolution $dE_{FWHM}/E = 18\%$ with

$$
\frac{dE_{FWHM}}{E} = \frac{2.35\sigma_{MP}}{SADC_{MP}}
$$

(5.2)

As mentioned above, using the $^{55}$Fe calibration the gas gain achieved thought the GEM can also be calculated. To do this, a test pulse is put into the PreAmp using the test input capacitor. The capacitor has a size of $C_{test}=100\text{fF}$. To achieve charge injection into the Preamplifier through the test capacitor a positive, square voltage pulse has to be put onto the capacitor. To achieve a well shaped output pulse with shaping time $4\mu\text{s}$, the square pulse should be positive and a few ms long.

When a test pulse is put onto the test capacitor a charge of the amount $\Delta Q=C_{test} \cdot \Delta V_{in}$ is injected into the PreAmp. $\Delta V_{in}$ corresponds to the height of the input pulse, or the change of voltage on the trailing edge of the input pulse. In the data this charge will now also correspond to an SADC count. Using this, one can calculate the charge conversion as:

$$
C_Q = \frac{C_{test} \cdot \Delta V_{in}}{SADC_{test}}
$$

(5.3)

Using $C_Q$ and the position of the $^{55}$Fe main peak in SADC counts, the charge that the main peak corresponds to can be calculated via

$$
Q_{5.9\text{keV}} = C_Q \cdot SADC_{5.9\text{keV}}
$$

(5.4)

Knowing that the main peak corresponds to a certain number of electrons $N_{e^-}$ as described before, this number of primary electrons and the charge collected on the readout board can be used to calculate the gas gain through the GEM, $G_{GEM}$:

$$
G_{GEM} = \frac{Q_{5.9\text{keV}}}{N_{e^-} \cdot q_{e^-}}
$$

(5.5)
Chapter 5. Detector calibration

To know the gain of the GEM is important for multiple reasons. First, it gives confidence that the detector is running well, since a drop in the gas gain will indicate either contamination of the gas or a possible break of the GEM. Second, the gain needs to be low for a neutron run, because neutron events tend to be much larger than the $^{55}\text{Fe}$ events and it needs to be taken care not to saturate the PreAmp. A lower gain also helps in keeping the GEM from breaking, since at high gains, larger amounts of charge are created which can potentially break the GEM during a neutron run.

The $^{55}\text{Fe}$ calibration is also important to calibrate the charge sharing between the X and Y strips for the 2D readout board. By measuring the position of the main peak in the SADC spectrum for both sets of strips, the charge sharing between X and Y strips can be determined by dividing the two positions of the main peak in SADC counts.

The fraction of charge that is collected by the X strips (and Y strips respectively) is given as

$$QS_{X(Y)} = \frac{SADC_{X(Y)}}{SADC_X + SADC_Y}$$  \hspace{1cm} (5.6)

If the strips are laid out optimally this charge sharing factor should be 50% for both sets of strips.

Two characteristic $^{55}\text{Fe}$ spectra are shown in Figure 5.4. They show the difference between the gains of the X and the Y strips. Relating the SADC’s of both spectra to one another results in the charge sharing being $QS_X=67\%$ and $QS_Y=33\%$. This is far from the optimal configuration of 50%. There is the possibility to take care of this difference by applying a slight voltage to the bottom strips and therefore forcing more field lines to them, which would even out the discrepancy in $QS_{X(Y)}$. However, the way the FEE boards were designed for the prototype detector, is such that the ground is shared between the X and the Y strips. Therefore, biasing one set of strips
Figure 5.4: Example of an $^{55}$Fe spectrum for the X and Y strips taken in 80torr CS$_2$ with $V_{GEM} = 460V$ and $E_D = 700V/cm$

to a certain voltage was not possible. Since having equal charge sharing on the X and the Y strips is not crucial to the experiments performed, the calculated factors for charge sharing on X and Y were used in the analysis. Care should be taken during the design of future detectors to allow for such a voltage bias.
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5.2 Calibration of the Strip-to-Strip gain using the calibration input on the PreAmp

The strip-to-strip gain of the PreAmp’s needs to be calibrated before a data run as well. This is not only due to the fact that multiple PreAmp chips are used which could slightly be different in their gains, but also the different channels on one PreAmp chip can have varying gains. To remove these gain variation a calibration needs to be performed.

To calibrate the strip-to-strip gain on the different channels, the test-pulse input on the PreAmp’s is used. It uses a 100nF capacitor to inject charge into a certain PreAmp channel. By applying a voltage difference on the test capacitor, the charge injected into that specific channel is given as

\[ Q = C_{\text{test}} \cdot \Delta V_{\text{in}} \] (5.7)

By injecting the same amount of charge into each PreAmp channel and reading it out through the WFD’s, the areas measured on each channel can be compared. A plot of the areas measured by injecting a 200mV test pulse into the capacitor for each channel is shown in Figure 5.5.

It can be seen here, that the gains vary up to about 10% in these measurements. The values used to adjust the strip-to-strip gain variations are listed in Table D.3. To adjust for these variations, the mean of the gain variations is computed and a relative gain factor on the i-th channel is calculated as

\[ \text{Relative gain factor} = \frac{\text{Measured gain}_i}{\text{Mean gain}} \]
Chapter 5. Detector calibration

Figure 5.5: Plot of the strip-to-strip calibration measurements. A test pulse of 200mV was used to inject charge into each PreAmp channel. Strips 1 to 16 correspond to the X strips and strips 17 to 28 correspond to Y strips. The changing gain can be seen and is adjusted accordingly.

\[ G_{rel,i} = \frac{\text{gain}}{\text{gain}_i} \]  

(5.8)

In the analysis, the calculated areas on each channel are then multiplied by this gain factor to adjust for the strip-to-strip gain variations. The reason to multiply the calculated areas under the pulse by this relative gain factor is, that these gains were found using areas.
Chapter 5. Detector calibration

Gain variations on each strip used to adjust strip-to-strip gains.

<table>
<thead>
<tr>
<th>Strip #</th>
<th>( G_{rel,i} )</th>
<th>Strip #</th>
<th>( G_{rel,i} )</th>
<th>Strip#</th>
<th>( G_{rel,i} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1X</td>
<td>0.914</td>
<td>9X</td>
<td>0.855</td>
<td>1Y,2Y</td>
<td>0.933</td>
</tr>
<tr>
<td>2X</td>
<td>1.159</td>
<td>10X</td>
<td>1.133</td>
<td>3Y,4Y</td>
<td>0.947</td>
</tr>
<tr>
<td>3X</td>
<td>0.915</td>
<td>11X</td>
<td>0.963</td>
<td>5Y,6Y</td>
<td>0.940</td>
</tr>
<tr>
<td>4X</td>
<td>1.114</td>
<td>12X</td>
<td>1.125</td>
<td>7Y,8Y</td>
<td>0.969</td>
</tr>
<tr>
<td>5X</td>
<td>0.907</td>
<td>13X</td>
<td>0.868</td>
<td>9Y,10Y</td>
<td>0.967</td>
</tr>
<tr>
<td>6X</td>
<td>1.071</td>
<td>14X</td>
<td>1.026</td>
<td>11Y, 12Y</td>
<td>1.009</td>
</tr>
<tr>
<td>7X</td>
<td>0.886</td>
<td>15X</td>
<td>0.854</td>
<td>13Y, 14Y</td>
<td>1.055</td>
</tr>
<tr>
<td>8X</td>
<td>1.096</td>
<td>16X</td>
<td>1.113</td>
<td>15Y, 16Y</td>
<td>1.034</td>
</tr>
</tbody>
</table>

The values for the strip-to-strip gains used are shown in table(). These are purely strip-to-strip gain factors not including any other gain adjustments made (e.g. the ones calculated from the \(^{210}\text{Po}\) source calibrations).

5.3 Calibration with \(^{210}\text{Po}\) source

A \(^{210}\text{Po}\) source decays to \(^{206}\text{Pb}\) by emitting \(\alpha\) particles. The \(\alpha\) particles have a characteristic energy of 5.407 MeV and the half life of the \(^{210}\text{Po}\) is 138.4 days. \(^{210}\text{Po}\) can also emit \(\gamma\) radiation in its decay, which has an energy of \(E=800\) keV, but this process is very rare (1 in 100,000 decays). The \(\gamma\) is emitted when the \(\alpha\) emission causes an excitation in the nucleus.

The reasons to calibrate the detector with \(\alpha\) particles are as follows. For one, the Bragg curves for the energy loss of an \(\alpha\) particle in gas are well known and can be calculated using the simulation tool SRIM (Stopping and Range of Ions in Matter) [55]. Therefore measuring these particles of known energy in the detector allows for calibration of the strip to strip gain uniformity. If it is known that the \(\alpha\) particle track across the X strips should create equal amounts of ionization on all strips, this can be used to calibrate the strip gains to be uniform across. Also, if the change in ionization is known, these tracks can be used to see how big an asymmetry of
Chapter 5. Detector calibration

charge can be measured with the detector at hand. This will give an indication if a head-tail asymmetry of a few percent in the nuclear recoil tracks can be resolved with the detector.

Using the program SRIM, the ranges and energy losses of alpha particles of a certain energy in 40, 80 and 120torr CS$_2$ can be simulated. The Bragg curve for a 5.407MeV $\alpha$ particle moving through 40 torr (80torr, 120torr) CS$_2$ can be seen in Figure 5.6. To generate these Bragg curves the following inputs to SRIM were used:

- Ion moving through the material: He atom ($\alpha$ particle)
- Ion Energy range lowest: 10keV, Ion Energy Range Highest: 5407keV
- Target: Carbon with “stoich” = 1; Sulfur with “stoich = 2”
- Density (g/cm$^3$): from ideal gas equation for CS$_2$: $\rho_{40torr}=1.667 \cdot 10^{-4}$, $\rho_{80torr}=3.334 \cdot 10^{-4}$, $\rho_{120torr}=5.004 \cdot 10^{-4}$
- Gas Target selected

To estimate the size of the effect that is expected, the setup of the source with respect to the strips needs to be considered. Figure 5.7 shows the detector inside the vessel with the $\alpha$ source placed next to the Y strips. The schematic in Figure 5.8 depicts the exact position of the source with respect to the X and Y strips and shows all the distances the $\alpha$ particle travels before crossing the X strips and leaving a signal. The $\alpha$ source itself is placed in a holder that is made out of acrylic and has a 0.5cm hole drilled all the way through to the source. A cap made of acrylic, which has a 0.05cm diameter hole is then placed on top of the holder. The holder itself is used for collimation of the $\alpha$ particles and the cap is used to chose additional, different collimation. With the hole in the cap being 0.5mm in diameter the maximum spread in the angle of the $\alpha$ particle is approximately 0.71°. The pinhole in the cap also
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Figure 5.6: Three Bragg curves calculated using SRIM in 40torr (blue), 80torr (red) and 120torr (pink) CS$_2$. The curves were calculated using 5.5MeV $\alpha$ particles moving through the gas. The region of the curve that would be observed on the X strips in the detector is found by going to the point furthest to the right on each curve and subtracting the distance to the X strips from this range value and finding the approximate position of this point in $dE/dx$.

limits the number of $\alpha$ particles entering the active detector volume, in this case it is expected that about 1 $\alpha$ particle interacts in the volume every 10s.

The source holder is approximately 3cm long and by the time the $\alpha$ particles will interact above the X strips in the detector, they will have traveled an extra 5 to 6 cm in the gas. Putting these numbers together, the particles will have traveled about 9cm in the CS$_2$ before reaching the X strips, therefore the interesting region in the Bragg curve for 40torr plotted in Figure 5.7 is at about 270mm (maximum range,
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Figure 5.7: 2D detector setup inside the vacuum vessel. The $^{210}$Po source is placed inside the plastic holder/collimator and positioned as seen in Figure(5.8).

360mm, minus the distance travelled, 90mm) and extends over a range of 3.2mm (the width of the active region above the X strips in the detector). It can be seen here that the region of the Bragg curve that will be seen in the detector is very flat. Therefore only a small change in the ionization across the strips is expected. Taking the numbers of ionization at the beginning and the end of the track from the Bragg curves, a total asymmetry of 1% is expected in 40torr CS$_2$:

$$asym_{40torr} = \frac{dE/dx(18cm)}{dE/dx(17.68cm)} = 1\%$$  \hspace{1cm} (5.9)

Since the position of the source inside the detector is not easily adjustable, the easiest way to get to different points on the Bragg curve (areas with higher slopes
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Figure 5.8: Schematic of the position of the the \( \alpha \) source with respect to the X and Y strips. The distances are measured and are used to calculate the asymmetry in charge along an alpha track using SRIM.

between the first and last strip hit) is by increasing the pressure of the gas. The relevant Bragg curves for these pressures are also plotted in Figure 5.6. It can be seen here, that the higher the pressure, the closer to the Bragg peak will the measurement be, which is due to the decreasing range of the \( \alpha \) particles in higher pressure gas. This means the slope of the line between two points 3.2mm apart will be steeper and therefore create a larger asymmetry in the charge.

The following asymmetries in charge between the first and last strip are achieved by increasing the pressure:

\[
asym_{80\text{torr}} = 3\%
\]  
(5.10)

\[
asym_{120\text{torr}} = 6\%
\]  
(5.11)
Chapter 5. Detector calibration

As mentioned before if the asymmetry of 6% for an $\alpha$ particle can be seen in the detector, then a small asymmetry in charge over a neutron track (such as resulting from a head-tail effect) is also expected to be seen.

5.3.1 Results from the $\alpha$ calibration

For the $\alpha$ runs, the trigger is set only on the odd X strips (1X, 3X, ..., 13X, 15X) and it is triggered on the sum of those channels as described in Section 3.5. The voltages on the GEM for the specific runs were $\Delta V_{GEM}(40\text{torr})=374\text{V}$, $\Delta V_{GEM}(80\text{torr})=368\text{V}$ and $\Delta V_{GEM}(120\text{torr})=414\text{V}$. The drift field was kept constant for all runs at $E_D \simeq 700\text{V/cm}$.

For all the runs, the $\alpha$ source was positioned in the detector as shown in Figures 5.8 and 5.7, therefore they would hit strip 16X first and strip 1X last. One run was performed in 40torr, 80torr and 120torr, which yielded about 1100 events for each pressure to analyze.

The data for all three runs was analyzed with the previously described analysis procedure. The strip-to-strip gains found from the calibration with charge injection described earlier were implemented in the $\alpha$ analysis. The thresholds and noise widths were also used. The cuts used for this analysis were

- **“track-length cut”:** This cut would remove events with “track$\rightarrow$ xstrips” $<16$. The tracks from the $\alpha$ particles are expected to cross the X strips completely due to their long range. This ensures any tracks that are not from $\alpha$’s are cut.
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Results from 40torr α calibration

The data for the $^{210}$Po run in 40torr CS$_2$ can be found in files 120704302008_210Po − x16_0 − 2D_v1.dat and 1039 events were stored. Out of these, 908 passed the analysis cut mentioned above (nstripsx<16). A characteristic α event is shown in Figure 5.9.

![Figure 5.9:](image.png)

Figure 5.9: The plot on the left shows an α event in 40torr CS$_2$ on the X strips. The plot on the right shows the event on the Y strips for the same event. The event shown is event number in the file 120704302008_210Po − x16_0_2D_v1.dat

It can be seen that the charge deposited on the Y strips is much larger than the charge on the X strips. This is due to the fact that the X strips sample a very small part of the track and will only see a very small amount of the total energy deposited. The Y strips on the other hand sample the entire track and therefore the entire energy deposited.

The first interesting thing to look at is the NIPs spectrum of the α run. Since the source is aligned with the X and the Y strips, the α’s are expected to only deposit a small amount of their energy on the X strips, but a very large amount on the Y strips, as they will hit only a few Y strips and due to their very small angular spread be mostly contained in Y. When looking at the NIPs spectrum for the X and Y strips
Chapter 5. Detector calibration

separately, one would therefore expect to see two peaks, one at lower energies in the X NIPs spectrum and one at higher energies in the Y spectrum. The spectrum on the X and the Y strips is plotted together in Figure 5.10.

![Figure 5.10: Characteristic NIPs spectrum on the X and Y strips for the $^{210}Po$ run in 40torr CS$_2$.](image)

The two peaks are nicely resolved and have a mean and a standard deviation of:

\[ \mu_X = 1.116 \cdot 10^5, \sigma_X = 2.201 \cdot 10^4, \Rightarrow \frac{\Delta E_{FWHM}}{E} \approx 12\% \]  
\[ \mu_Y = 1.642 \cdot 10^5, \sigma_Y = 8.673 \cdot 10^4, \Rightarrow \frac{\Delta E_{FWHM}}{E} \approx 46\% \]

This result gives confidence that the regions in the $\alpha$ tracks that are sampled by the detector are the same for all of the events analyzed and will therefore lie in the same region on the Bragg curve.
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As mentioned above the asymmetry in the $\alpha$ track over the 3.2mm X strip region should be about 1%. If measuring the asymmetry of the track using the charge on the first eight strips in X ($Q_L = \sum_{i=0}^{7} q(i)$) and the last eight strips in X ($Q_R = \sum_{i=8}^{15} q(i)$) via

$$ asym = \frac{Q_L - Q_R}{Q_L + Q_R} $$

(5.14)

the expected asymmetry is even smaller at $<1\%$.

Since the asymmetry is so small it is fair to assume that if the average charge on each strip is plotted with respect to strip number, the resulting distribution should be flat. A plot of the average charge on each strip from the 40torr run can be seen in Figure 5.11.

The black curve plots the average charge ($q_{av}(i)$) on strip $i$, calculated by adding the charge on each strip for each event and then dividing by the number of events. This is done for all the events that pass the cut mentioned above.

Since it is known that this distribution should be flat across all 16 strips, a gain factor $g_\alpha$ is calculated as

$$ g_\alpha(i) = \frac{q_{av}(i)}{\sum_{i=0}^{15} q_{av}(i)} $$

(5.15)

These gains are then added in the TFEvent.cc subroutine with the strip to strip gains calculated before. The complete gain on each strip is then calculated by multiplying the $\alpha$ gains $g_\alpha(i)$ with the strip-to-strip gain obtained from charge injection $g_{injection}$ discussed before.

To check that these gains give the right result, the analysis is ran again on the 40torr files with the $\alpha$ gains implemented. This results in the red curve in Figure 5.11 which is now completely flattened out. The asymmetry in equation 5.14 can
Chapter 5. Detector calibration

Figure 5.11: Average charge on each strip in X from the α calibration run in 40torr CS$_2$. In black the average charge is shown before the strip gains were adjusted and in red is the average charge on each strip after adjusting the strip gains to flatten out this distribution.

also be plotted before and after the α gains are introduced. They are plotted in Figure 5.12.

Fitting a Gaussian to both distributions, the means and the standard deviations are:

$$\mu_{before} = -0.015, \sigma_{before} = 0.132, \Delta \mu = \frac{\sigma}{\sqrt{N}} = 0.004 \quad (5.16)$$

$$\mu_{after} = 0.002, \sigma_{after} = 0.132, \Delta \mu = \frac{\sigma}{\sqrt{N}} = 0.004 \quad (5.17)$$

The asymmetry became even smaller by applying the new gains in the analysis.
Figure 5.12: Asymmetry asym$_{40}$ plotted for 40torr $^{210}Po$ run before (black) and after (red) the strip gains were adjusted with $g_\alpha$

This was expected, since the whole idea behind applying them was to zero out the asymmetry. Now the 80 torr and 120torr data needs to be checked to see if the larger asymmetry discussed above can be seen. $N$ is the number of events that are analyzed and is given here as $N = 908$.

**Results from 80torr $\alpha$ calibration**

The setup for the $\alpha$ run in 80torr is exactly the same as for the 40torr run, only the pressure has been increased. The voltages on the GEM and resulting fields are as mentioned above. The files containing the data are
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“024205012008_Po210-x16.(0 to 2)_2D.v1.dat”. A plot of the strip gains and the asymmetries before and after the $\alpha$ gains were introduced are shown in Figure 5.13.

![Average charge on strips](image1.png) ![Charge Asymmetry](image2.png)

Figure 5.13: Average charge per strip and asymmetry asym$_{80}$, plotted for 80torr $^{210}$Po run after the strip gains were adjusted with $g_\alpha$.

The average strip charge now is slightly falling from strip 1X to strip 16X as it should. The asymmetry is still nicely Gaussian and can be fitted to reveal the extent. The mean and standard deviation of the asymmetry in 80torr CS$_2$ are

$$
\mu_{after} = -0.0055, \quad \sigma_{after} = 0.0850, \quad \Delta \mu = \frac{\sigma}{\sqrt{N}} = 0.0028
$$

Here the number of events was $N = 933$, which was used to calculate the error of the mean, $\Delta \mu$. The asymmetry is smaller after adjusting the gains, but is larger than it was at 40torr. Since the asymmetry is expected to be still very small in 80torr pressure, it is not clear what conclusions can be drawn from this.

Results from 120torr $\alpha$ calibration

The setup for the $\alpha$ run in 120torr is the same as for the 40torr run with increased pressure. The voltages on the GEM and resulting fields are as mentioned above. The
files containing the data are “092505022008_Po210-x16_(0 to 2)_2D_v1.dat”. A plot of the strip gains and the asymmetries before and after the \( \alpha \) gains were introduced are shown in Figure 5.14.

![Figure 5.14: Average charge per strip and asymmetry asym\(_{120}\) plotted for 120torr Po run after the strip gains were adjusted with g\(_\alpha\).](image)

The average strip charge now is slightly falling from strip 1X to strip 16X as it should. The asymmetry is still nicely Gaussian and can be fitted. The mean and standard deviation of the asymmetry in 120torr CS\(_2\) are

\[
\mu_{\text{before}} = -0.015, \quad \sigma_{\text{before}} = 0.0551, \quad \Delta \mu = \frac{\sigma}{\sqrt{N}} = 0.0017
\] (5.19)

Here the number of events was \( N = 1037 \), which was used to calculate \( \Delta \mu \).

The asymmetry is also smaller after adjusting the gains, but again is larger than the asymmetry in 40torr and 80 torr. This gives confidence that a small asymmetry in the charge across a nuclear recoil track can be seen as well.

As discussed earlier, the \( \alpha \) runs enabled a strip-to-strip calibration that was not found from the charge injection procedure. It has also been shown that using these new gains, an asymmetry of a few percent can be seen in the 120torr data.
Chapter 6

Preliminary measurements

Different preliminary measurements had to be performed before the detector could be used to measure the low energy nuclear recoil tracks it was designed for. These measurements are done to determine the electron diffusion in 40torr CS$_2$ and to confirm the drift velocity of the negative ions. A control measurement with $\gamma$ particles from a $^{60}$Co source was performed as well. The $\gamma$ measurements were performed to determine the detection efficiency for $\gamma$ particles using the detector setup and analysis procedure described. The results of these measurements are all described in this chapter.

6.1 Measurement of electron diffusion in CS$_2$

In electric fields less than 1000V/cm, as used in the drift volume of the detector, the charge carriers in CS$_2$ are negatively charged ions. The diffusion of the negative ions is well known, which has been discussed in Chapter 2, Section 2.4.2. The diffusion
of negative ions in CS$_2$ is given by the following equation:

$$\sigma_{CS_2} = 0.72 \text{mm} \cdot \sqrt{\left(\frac{d}{1m}\right) \cdot \left(\frac{1\text{kV/cm}^{-1}}{E}\right)}$$  \hspace{1cm} (6.1)

In this equation, $\sigma_{CS_2}$ is the width of the Gaussian that a delta function charge distribution of negative ions would diffuse into in an electric field $E$ (in kV/cm) over a distance $d$ (in m). The derivation of this equation, as well as a discussion of electron diffusion, can be found in Section 2.4.2.

Using Equation (6.1), the expected diffusion over a certain drift distance inside the active detector volume can be calculated. When the negatively charged ions enter the high field region of the GEM, the electrons are stripped off the ion and the now positive ion drifts back upwards towards the cathode. The electrons avalanche multiply in the GEM holes and are transferred through the transfer region to the readout strips as described in Section 3.7. In the transfer region, the field is chosen to be very high ($>2500\text{V/cm}$) to not allow the electrons to reattach to the CS$_2$. That means, in the transfer region, the primary charge carriers will be the electrons.

Since the diffusion of electrons in CS$_2$ is not easily calculated or simulated, a method for measuring this diffusion needed to be developed. This was necessary to ensure that the electron diffusion in the transfer region is small enough, that it would not dominate and therefore remove the inherent structure of the charge distribution along the track. It is also important to know if the transfer field is big enough to keep electron diffusion low such that it can be chosen as far away from breakdown as possible.

### 6.1.1 Experimental setup

To measure the diffusion precisely, a source of ionization is needed that can create a delta function of charge or at least has a well known dimension associated with
Chapter 6. Preliminary measurements

It. There are different ways of achieving this goal. One approach, used by the NEWAGE collaboration, uses a 1GeV/c $\pi^-$ beam to create ionization in the drift region [56]. The problem with this approach is, that the distance from the ionization to the multiplication stage might not be known very well and will therefore introduce a systematic error to the measurement. A particle beam of this sort was also not available at the time of the presented measurements.

It was therefore decided to use a different approach. The setup chosen uses a gold coated tungsten wire of 20$\mu$m diameter that was strung through the drift volume between the cathode and the top of the GEM in the previously described 1D detector setup. A nitrogen laser of characteristic wavelength $\lambda = 337$nm is then aligned to hit the wire. The light, hitting the wire, will create free electrons from the wire through the photoelectric effect. The work function of the gold coating the wire is 4.7eV-5.1eV, which is greater than the energy that can be deposited by one photon from the laser, which is $E_\gamma = 3.682$eV. This gives an important advantage in making the measurement. The laser has to be focused tightly onto the wire to create free electrons via two photon effects. In turn, this means, that scattered, incoherent light from the wire will not be able to create free electrons on any other surface inside the detector (Cu GEM surface, Cu cathode, stainless steel vessel interior wall, etc.).

The specific detector setup for this measurement is shown in Figure 6.1. The schematic shows how the wire is setup between the GEM and the cathode and the position of the labjack used to adjust the drift distance from the wire to the GEM. By changing the distance between the wire and the GEM, the distance the ions have to drift is increased or decreased and therefore the width of the negative ion diffusion is changed as seen in Equation (6.1).

The wire is inserted in the detector setup such that it is parallel to the strips, as seen on the right in Figure 6.1. The reason to align it this way is that the laser spot is not a point, but has finite width $\sigma_{laser}$. If the wire was aligned perpendicular to
Chapter 6. Preliminary measurements

![Detector assembly schematic](image)

Figure 6.1: The detector assembly for the diffusion measurements is shown on the left. On the right, the alignment of the wire over the strips is shown. In the actual setup, the wire is most likely not aligned as perfectly as shown here.

the strips, this $\sigma_{laser}$ would be the initial width of the charge distribution and would complicate the measurement of $\sigma_{diffusion}$. If aligned as shown above, the initial distribution will not depend on the width of the laser spot.

The wire strung through the drift volume of the detector is connected to an additional powersupply placed outside the vessel. The connection is made through a high voltage (HV), hermetic feedthrough directly to the wire.

A picture of the optical setup outside of the vessel is shown in Figure 6.2 and a schematic of the entire setup and a ray diagram of the laser is shown in Figure 6.3. All the optical equipment seen in the picture is used to focus a clean, Gaussian profiled beam onto the wire.

One of the problems with the nitrogen laser used in the experiments, was that the beam created did not have a nice Gaussian shape. After further investigation, the shape of the beam profile had to be attributed to an unaligned cavity. Since the laser could not easily be repaired, a different solution was needed. To force the shape
Figure 6.2: Setup of the vessel, the laser and all the optical components needed to focus the laser onto the wire. The two lenses and the pinhole needed to create a Gaussian beam profile can be seen directly next to the laser on its left side. The large lens seen before the vessel is used to focus the beam onto the wire.

of the laser beam into a Gaussian profile, a pinhole of diameter $100\mu m$ was set into the path of the laser beam. Two lenses of short focal length were used to first focus the laser beam onto the pinhole and then collect the light behind it and return it to parallel light beams. This resulted in some loss of intensity of the laser beam, but the now Gaussian beam profile was easier to focus. The setup for this can be seen on the right side in the photograph in Figure 6.2, between the laser and the vessel.

The large lens that can be seen directly in front of the vessel was a large focal length lens. It was used to focus the light onto the wire from outside the vessel. The focal point was aligned slightly behind the wire. This way, the shadow of the wire could be seen in the laser light that was projected through the vessel onto the wall behind the experiment. To allow the laser light into and back out of the vessel, two UV transmitting windows were used.
Figure 6.3: Schematic of the setup for the diffusion measurements, showing the laser beam and how it is aligned in the setup.

The lens used to collect the laser light after the pinhole was mounted inside a special holder that allowed for movement of the lens in all three spatial directions. This way, the laser beam could be adjusted to either hit the wire and create photoelectrons in the detector or moved off the wire, and therefore going straight through the experimental setup without creating charges off the wire. This allowed for data taking with the laser “on” (hitting the wire) and the laser ”off” (not hitting the wire).

For the measurements of the diffusion and drift velocity, the 1D detector was used exclusively, since the diffusion will be symmetric in the x-y plane and all the extra information from the 2D detector was not needed.

### 6.1.2 Poisson field simulations

One of the complications of this measurement that needs to be mentioned is that the wire has to be at exactly the right potential $V_W$, which is calculated from

$$V_W = (V_C - V_{top,GEM}) \cdot \frac{d_{WG}}{d_{CW} + d_{WG}}$$

(6.2)
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where $V_C$ is the potential of the cathode, $V_{\text{top,GEM}}$ is the voltage on the top surface of the GEM and $d_{WG}$ and $d_{CW}$ are the distances from the wire to the top GEM surface and the from the cathode to the wire respectively.

The software package “Poisson Superfish” [57] is used, to find out what happens to the field lines and the equipotential lines between the cathode and the GEM when the wire is introduced. A characteristic output is shown in Figure D.11 in Appendix D. It shows the case when the wire is set at the exact potential $V_W$ as calculated using Equation (6.2).

Since the voltages are only known precisely to a couple of volts ($\Delta V = 5V$) and the distances to about 1mm ($\Delta d = 1mm$), the error on this calculated voltage would be

$$
\Delta V_W = \frac{d_{CW}}{d_{CG}} \sqrt{2\Delta V^2 + (V_C - V_t)\Delta d^2 \left[ \frac{d_{CW}^2 + d_{CG}^2}{d_{CW}^2 \cdot d_{CG}^2} \right]} 
$$

(6.3)

The size of this error will be discussed and estimated in more detail later.

The geometry modeled in Poisson assumes the cathode and the GEM as simple parallel plates at potential. The dimensions for both are 10cm by 10cm. The wire is modeled as a circle of diameter 20$\mu$m at the distances chosen from the top GEM surface (10mm and 21mm, see Section 6.1.3). The program is then used to calculate the equipotential and field lines for this geometry. The output is a plot of the geometry including the field and potential lines, as shown in Figure D.11. It can be seen here that the electric field is slightly disturbed around the wire, with field lines going into and coming off of the wire. The equipotential lines can also be seen to be disturbed. The disturbances are rather small and disappear about two wire diameters away from the wire. Outside of that region, the electric field and the equipotential surfaces are undisturbed.
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This confirms that the wire does not significantly disturb the electric field in the drift region and allows for using this method. It can be assumed that charges created from the wire will start out as point charges in the same electric field that can be found in the rest of the detector.

One of the problems with this setup occurs when the potential on the wire is not set at exactly the right value. If, for example, the distances are only known to 1mm precision, the potential on the wire might be set higher or lower than it should be. Using “Poisson”, this scenario can be simulated. Therefore, various plots had to be generated that use a higher and a lower $V_W$ than calculated. Two examples of these plots are shown in Figure D.12 and Figure D.13 in Appendix D and they show what happens to the field and equipotential lines when the voltage on the wire is larger or smaller than it should be. The two shown cases are extremes of this situation to allow for easier identification of the arising issues.

It can be seen that in the case of the voltage being too low (Figure D.13), the equipotential line around the wire is pushed up further around the wire. All the fieldlines can be seen to now be going towards the wire, until about two wire diameters away from the wire. This means, that charges created around the wire will be artificially attracted back to the wire in the electric field. This might have a focusing effect on the charge that actually escapes from the wire, as it would not end up as far away from the wire as it should have been. It is believed that this will decrease the measured diffusion from the expected diffusion.

When the voltage on the wire is too high (Figure D.12), the equipotential lines will be pushed down and not go straight around the wire. This will lead to electric field lines being predominantly directed away from the wire. This could lead to an artificial spread of the created charge cloud due to the fact that the field lines going away from the wire will push some charges further out into the drift region than they would have normally spread. This would increase the measured diffusion.
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How these two cases affect the measurements presented below is mentioned in detail when applicable.

6.1.3 Measurements

Different measurements were performed with the detector setup described above. The first two sets of measurements were done in 500torr ArCo\textsubscript{2} and in 510torr CF\textsubscript{4}. In both gases the electrons are the only primary charge carriers (in the drift as well as the transfer region) and will drift in the electric fields. The reason to start with these two gases is that the electron diffusion in both is well known and can be calculated using the software package “Magboltz” [58]. This will allow for checking, that the measured diffusion is equal to the calculated diffusion and therefore allow for benchmarking the measurement method.

The third set of measurements was done in 40torr CS\textsubscript{2}. As mentioned before, the electron diffusion in this gas is not easily calculated or simulated, but with the two previous measurements, an assessment can be made, if the electron diffusion is too large to significantly limit the desired measurements of the fundamental properties of the low energy nuclear recoil tracks.

Electron Diffusion in ArCo\textsubscript{2}

To measure the electron diffusion in ArCo\textsubscript{2}, the vessel was filled with ArCo\textsubscript{2} at a pressure of 500torr and the experiment was set up as described above. The alignment of the laser onto the wire was performed by adjusting the lenses and watching for the shadow of the wire to appear in the projection of the laser spot on the wall.

After aligning the laser, the voltages on the GEM were set to $\Delta V_{GEM} = 470V$. The voltage on the GEM was kept constant throughout the experiment but the
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voltage on the cathode was adjusted to allow for measurements of the diffusion in different drift fields $E_D$. Also, as mentioned before, the drift distance from the wire to the GEM was adjustable and therefore the results presented are the width of the diffusion as a function of electric field plotted for two different drift distances.

The way the measurements were performed is as follows. The voltages on the GEM and the cathode were set. Then the laser was turned on and pulsed at a rate of about 1Hz. 100 events were then recorded using the WFD and data acquisition software. The pulse heights of these events were histogrammed and a Gaussian distribution fitted to them. The mean $\mu_{PH}$ was then plotted for each strip which can be seen in Figure 6.4.

After plotting the average pulseheights, a Gaussian was fitted to the distribution and the $\sigma$ of the Gaussian represents the $\sigma$ of the diffusion, since it is assumed here that the charge created from the wire by the laser has a $\delta$-function distribution. If this is a good approximation will be discussed in more detail later on.

The process of measuring the spread $\sigma$ of the charge distribution is then repeated for multiple drift fields $E_D$ and later on for another drift distance. The results from the measurements in ArCO$_2$ for a drift distance of $d_{WG} = 21\, mm$ are shown in Figure 6.5.

It can be seen here, that the experimental results agree very well with the results for the diffusion obtained using “Magboltz”. This gives confidence that the assumptions made above are valid and the experimental setup can be used to realistically estimate the diffusion of electrons in CS$_2$.

A second measurement was performed in 500torr ArCO$_2$ with a drift distance of $d_{WG} = 10\, mm$. This is important, as the stability of the measurement needs to be tested. As before, the width of the diffusion for a 10mm drift distance is plotted versus drift field in Figure 6.6.
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Figure 6.4: Strip number versus average pulseheight ($\mu_{PH}$) with a fitted Gaussian to the distribution. The electric field for this plot was $E_D = 440\text{V/cm}$ and the drift distance was 14mm. This measurement was taken in CF$_4$

It can be seen here that the first two points on this plot from the measured data do not agree well with the simulated diffusion. There are various reasons for this discrepancy. As mentioned before, if the distance between the wire and the top surface of the GEM is not known very well, the potential applied to the wire will not be optimal. This will be more dramatic when the drift distances and drift fields are small. Depending on the sign of the difference $V_{optimal} - V_{actual}$, this will change the diffusion, either make it better (since the fields will be acting as focusing) or make the diffusion worse (fields will act as spreading the charge). It can be seen in Figure 6.6 that the diffusion was smaller than expected. Since there will always be an error
on how precise the drift distance can be measured, these discrepancies are expected at low $d_{WG}$ and $E_D$.

As a result of this measurement, it was decided to not decrease the drift distances below 20mm in the following measurements. Therefore, the short drift distance measurement at 10mm is not repeated in CF$_4$ or CS$_2$. 

Figure 6.5: Width $\sigma$ of the electron diffusion in ArCO$_2$ versus drift field $E_D$ for a drift distance of $d_D = 21$mm. The blue points represent the measured data and the magenta curve represents the values calculated using Magboltz. There is very good agreement of the results with simulation.
Figure 6.6: Width $\sigma$ of the electron diffusion in ArCO$_2$ versus drift field $E_D$ for a drift distance of $d_D = 1.0$cm. The blue points represent the measured data and the magenta curve represents the values calculated using Magboltz. It can be seen that at lower electric field values the measured diffusion seems to be smaller than the simulations predict. It was later realized that the distance from the wire to the GEM was smaller than measured and that the wire potential might have been chosen too large and therefore caused an inaccurate measure of $\sigma$.

**Electron Diffusion in CF$_4$**

Another cross check of the diffusion measurement can be obtained by repeating the previous measurement in CF$_4$. This gas, as is ArCO$_2$, is also a non-electronegative gas and therefore allows for easy calculation of the electron diffusion. The measurement performed here is used as a cross check, that the diffusion in a different gas can be measured as well and also explores possible other effects that are not present in ArCO$_2$. 
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The measured width of the diffusion is plotted with respect to the drift field $E_D$ and compared to the simulated results, which is shown in Figure 6.7.

Figure 6.7: Width $\sigma$ of the electron diffusion in CF$_4$ versus drift field $E_D$ for a drift distance of $d_D = 2.03$cm. The measured data is plotted in blue and the values calculated using Magboltz is plotted in pink. It can be seen that at lower electric field values the measured diffusion seems to be smaller than the simulations predict. It was later realized that the distance from the wire to the GEM was smaller then measured and that the wire potential might have been chosen too large and therefore caused an inaccurate measure of $\sigma$

It can be seen, that the measured results give a considerably higher diffusion than the simulated results for fields larger than 100V/cm. This effect can be attributed to different things. For one, as described earlier, the voltage on the wire might not be measured correctly. The distance was remeasured after the data taking run and was indeed found to be measured incorrectly. Adjusting for this still does not change the large offset of the measured data from the simulations.
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Another effect can be that the assumption of the initial charge distribution to be a δ-function is not correct. It has been discussed in [56] that the initial charge distribution needs to be considered to calculate the actual diffusion in CF$_4$. This can be done the following way. When plotting the measured diffusion $\sigma_{\text{meas}}$ versus the drift distance in a particular electric field, it will be given as

$$\sigma_{\text{meas}}^2 = \sigma_{CD}^2 + \sigma_{d}^2 \cdot d_{WG} + \sigma_{dt}^2 \cdot d_t$$

(6.4)

where $\sigma_{CD}$ is the initial width of the charge distribution from the wire before diffusion, $\sigma_{d}$ is the transverse diffusion coefficient, found from the slope of the fitted line, $\sigma_{dt}$ is the width of the diffusion introduced in the transfer region of the detector and $d_t$ is the distance from the bottom of the GEM to the readout board. The plot of the measured charge distribution versus drift distance and the linear fit for one drift field is shown in Figure 6.8.

Once the width is measured, the width of the initial charge distribution can be extracted from the point where the linear fit intersects with the y axis. The distance $d_t$ is 3mm and the spread of the diffusion in the transfer region is taken from “Magboltz” at 3000V/cm transfer field. This way the initial charge distribution can be calculated and is found to be on the order of 100$\mu$m for lower fields and decreases for the higher fields.

The width of the diffusion is found from the slope of the fitted line (using the newly measured $d_{WG}$ and is plotted in Figure 6.7 as the green points. Again, there is a shift of the points upwards from the expected diffusion. But this corrected result is now much closer then the previous measurement without this correction on the initial charge distribution. It is believed that this is due to an error in the measurement of the drift distance, but the two results are close enough and the measurement was not repeated.
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Figure 6.8: Measured width of diffusion versus drift distance in mm together with the linear fit. This data is taken for a fixed drift field of $E_D =$.

Electron Diffusion in CS$_2$

The previous two measurements were convincing that the method used will allow for a determination of the electron diffusion in CS$_2$ to the point where the result might sustain a shift from the previously described problems with the measurement. But it will allow for a determination of the size of the effect and give an indication if the electron diffusion is likely to mask any interesting effects in the recoil measurements.

Figure 6.9 shows a plot of the pulse height in mV plotted with respect to the strip number, for a drift field $E_D = 700V/cm$, at a drift distance of $d_{WG} = 22mm$ in
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Figure 6.9: Measured width of diffusion in 40torr CS$_2$ at $E_D = 700V/cm$ and $d_{WG} = 22mm$.

40torr CS$_2$.

The diffusion measured at this particular drift field and drift distance is

$$\sigma_d = 220\mu m, \quad \sigma_{calc} = 700\mu m \cdot \sqrt{\frac{0.02159}{0.7}} = 123\mu m$$  \hspace{1cm} (6.5)

Even if the expected diffusion is about 100$\mu m$ lower than the measured diffusion, this result still gives confidence that the maximum diffusion of one strip at the given voltage and drift distance is small enough to not affect any of the measurements that were performed subsequently.
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To measure a different point of the electron diffusion in CS\(_2\), a different transfer field \(E_t\) would have been needed. Since this is rather hard to change, the achieved result was considered sufficient to move to a next set of measurements and not repeat this one for different fields \(E_t\) or \(E_D\) or changed drift distances \(d_{WG}\).

It may be noted here, that for the measurements of the nuclear recoil tracks, drift fields of 700V/cm were usually used and drift distances no larger than 2cm were employed, so the expected diffusion should be less then the measured 220\(\mu m\).

### 6.2 Drift velocity measurements in CS\(_2\)

The setup of the wire could also be used to measure the drift velocity of the ions in 40torr CS\(_2\). To do this, the wire is exposed to the pulsed laser once again. Instead of measuring the resulting signal from the strip readout, the GEM was used in the GEM readout setup. The voltage across the GEM for these measurements was set at \(\Delta V_{GEM} = 430V\) and the drift fields were varied by adjusting the voltage on the cathode. The top of the GEM was kept at ground potential.

The drift distance for this measurement was set at \(d_{WG} = 21.59 mm\). To calculate the drift distance, the time between the trigger of the laser and the onset of the pulse on the oscilloscope was measured. The point in time chosen at the beginning of the pulse was equal to 10% of the pulseheight. To calculate the drift velocity \(v_D\) the drift distance \(d_{WG}\) was divided by the time difference \(\Delta t\). The drift velocity was then plotted with respect to the drift field, which can be seen in Figure 6.10.

The measured drift velocities are somewhat controversial within the DRIFT collaboration. Drift velocities in 40torr CS\(_2\) have been measured by various members of the collaboration. Two different methods to measure the velocity were used, one using a similar approach, by creating photoelectrons at a cathode in a drift chamber
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![Drift velocity, 40torr CS$_2$](image)

Figure 6.10: Drift velocity in 40torr CS$_2$ as measured with the wire setup for different drift fields.

[59] and the other is using α particles [60]. The controversy arises, since the measured drift velocities are consistently larger than the ones measured by other members of the collaboration.

Certain errors can be assigned to the results presented above. The various values and an estimate of their error are:

- **Drift distance**: obvious choice, since at has been seen before that this influences the parallelness of the drift field through its impact on the wire potential; possible error $\Delta d_{WC} = 1mm$, anything larger than this would be impossible to miss.
- **Drift time**: The drift time could be measured differently, for example at the
“full width at half maximum” (FWHM) point or the peak; the peak time will not be considered since a definition of this does not seem to be sensible; when moving the arrival time to the FWHM an error on $\Delta t$ could be introduced of $\Delta(\Delta t) = 2\% \Delta t$

- Drift field: The drift field could have an error and therefore one might expect to see drift velocities measured as high, since $E_D$ is actually larger; the drift field would be assumed wrong if the distance between the cathode and the GEM was not well known or the voltage from the power supply to the cathode was changed; these errors are assumed as $\Delta d_{CG} = 1mm$ and $\Delta V_C = 2V$; using these numbers the error in the drift field would be $\Delta E_D 3\% E_D$

Implementing all these errors into the calculation of the drift velocity, the possible error on $v_D$ is

$$\Delta v_D = 5\% v_D$$ (6.6)

This error is not large enough to explain the rather big discrepancy between the results. This controversy still exists to date.

### 6.3 Calibration with $^{60}$Co source

A run with a $\gamma$ source was performed to explore the contamination of the neutron exposures with $\gamma$ particles that might influence the measurements of the fundamental track properties as desired. The $\gamma$ source used is a $^{60}$Co source that decays by emitting a 0.31MeV $\beta$ particle and then two successive $\gamma$ particles of energies 1.17MeV and 1.33MeV. The decay product is $^{60}$Ni and the half life of the $^{60}$Co is 5.27 years. The activity of the $^{60}$Co source when it was first assessed on
11/15/1986 was $A_{\text{Co1986}} = 100\mu Ci$. This means that at the time the measurements with the $^{60}\text{Co}$ source were taken in June 2008, this activity has decreased to $A_{\text{Co2008}} = 5.790\mu Ci = 2.142 \cdot 10^5 \text{decays/s}$.

The $^{252}\text{Cf}$ source used in the neutron exposures in Chapter 7 also produces $\gamma$ particles in the fission process. Roughly six $\gamma$’s are produced for every fission neutron [61] and they have a spectral energy distribution that peaks at about 1MeV. A spectrum of the $\gamma$ particles produced in the spontaneous fission process of the $^{252}\text{Cf}$ source is shown in Chapter 7, Figure 7.3.

To expose the detector to the $\gamma$ rays from the $^{60}\text{Co}$ source, it is placed perpendicular to the X strips on the outside of the vessel. This is the same position the neutron source would be placed for a X directed run. The $^{60}\text{Co}$ source was also placed on top of the detector in the same position the neutron source was placed for a Z down directed run. For the $\gamma$ source run, no lead shielding is placed in front of the source to allow the $\gamma$ particles to enter the detector without decreasing the number of $\gamma$’s. Lead shielding is placed around the source to protect from the radiation.

Data was taken with the $^{60}\text{Co}$ source in June 2008. These runs were performed in 80torr and 120torr of $\text{CS}_2$ and the source was placed to create $\gamma$ events along the X1 and the Z down directions discussed in Chapter 7. The available data from these runs is listed in Table D.1 in Appendix D. A background run was also performed during the $\gamma$ runs, which was taken with the $^{60}\text{Co}$ source removed and stored far away from the detector. This run is also listed in Table D.1.

The analysis cuts chosen for the all the $^{60}\text{Co}$ runs are

- **“containment cut”:** The charge on the first and the last strip in X had to be less than 30NIPs ($q_0$ and $q_15 < 30$). The same cut is used in the analysis of the neutron data.
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Table 6.1: Available data from the $^{60}$Co run showing how many events were left after the cuts introduced above were applied to the data.

<table>
<thead>
<tr>
<th>Direction</th>
<th>P (torr)</th>
<th>Tot. Events</th>
<th>Events after ana ($\geq$200NIPs)</th>
<th>Events after ana ($\geq$500NIPs)</th>
<th>$\Delta t$ (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>80</td>
<td>1122</td>
<td>72</td>
<td>0</td>
<td>30.833</td>
</tr>
<tr>
<td>Z down</td>
<td>80</td>
<td>4183</td>
<td>370</td>
<td>8</td>
<td>63.233</td>
</tr>
<tr>
<td>X1</td>
<td>120</td>
<td>318</td>
<td>43</td>
<td>3</td>
<td>20.133</td>
</tr>
<tr>
<td>Z down</td>
<td>120</td>
<td>161</td>
<td>23</td>
<td>0</td>
<td>22.083</td>
</tr>
<tr>
<td>background</td>
<td>80</td>
<td>53</td>
<td>3</td>
<td>0</td>
<td>2.400</td>
</tr>
</tbody>
</table>

- **“total charge cut”**: The total charge of the track had to be larger than 200NIPs. This is slightly lower than the total charge cut used on the neutron data (there it is 500NIPs).

- **“broken-track cut”**: This cut removes tracks that have strips inside a track with no charge on them. One of these strips would be acceptable, but if there are more than one strip with no charge in a track the event is cut. This cut is also used in the neutron data analysis.

Using these cuts, which are the same as the cuts used on the neutron data, it allows for estimating the amount of $\gamma$ contamination in the neutron data. The reason to chose a lower “total charge cut” is to be able to show where most of the $\gamma$ events produce tracks in a 2D range versus NIPs plot. The two dimensional range is calculated in the secondary analysis and can be found as $track \rightarrow R2$. The total charge in NIPs of a track is found as $track \rightarrow qnips$ in the data.

The number of events that pass the analysis cuts introduced above for each run is shown in Table 6.1.

A 2D range versus NIPs plot from an X directed $^{60}$Co run in 80torr CS$_2$ is shown in Figure 6.11.

With the charge threshold at 200NIPs, 72 events out of the total 1122 event
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Figure 6.11: Two dimensional range versus NIPs plot for X directed $\gamma$’s from a $^{60}$Co source in 80torr CS$_2$. A total of 1122 events were collected and 72 passed the analysis cuts with a 200NIPs charge threshold.

collected pass the analysis. When the qnips cut is increased to 500NIPs, no events pass the analysis.

The same analysis is performed on the Z directed runs in 80torr CS$_2$ and both runs in 120torr. The 2D range versus NIPs plots for these three runs are shown in Figures 6.12 6.13 and 6.14.

The results from the runs with the $^{60}$Co source will become important in Chapter 7, when they will be used to calculate the expected amount of $\gamma$ particle contamination in the neutron data. To do so, it is also important to know how many $\gamma$ events were expected to be seen from the $^{60}$Co source. How this is done is shown in the following section.
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6.3.1 Expected event rate from $^{60}\text{Co}$ $\gamma$’s

To investigate how the measured number of $\gamma$ events in the detector relates to the expected rate, it can be estimated how many $\gamma$ particles are expected to create a track inside the active detector volume.

When the $^{60}\text{Co}$ source was first purchased in November 1986 its activity was measured to be

$$A(11/15/1986) = 100\mu Ci$$ (6.7)

$^{60}\text{Co}$ has a half life of $T_{1/2} = 5.271$ yrs, so the activity of the source in June 2008 had
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Figure 6.13: Two dimensional range versus NIPs plot for X directed $\gamma$'s from a $^{60}$Co source in 120torr CS$_2$. A total number of 318 events were collected out of which 43 passed the analysis cuts at 200NIPs.

decayed to

$$A(06/2008) = 5.790\mu Ci$$  \hspace{1cm} (6.8)

It was mentioned above that the source was placed in exactly the same positions as the neutron source later on. This means, the distances from the source to the active detector volume were as follows

$$d_{X1,X16} \simeq 28cm$$  \hspace{1cm} (6.9)

$$d_{Zdown} \simeq 18cm$$  \hspace{1cm} (6.10)

$$d_{Zup} \simeq 15cm$$  \hspace{1cm} (6.11)
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Figure 6.14: Two dimensional range versus NIPs plot for Z directed $\gamma$'s from a $^{60}$Co source in 120torr CS$_2$. A total of 176 events were collected and 23 passed the analysis cuts with a 200NIPs charge threshold.

Using these numbers, the number of $\gamma$ particles that are actually emitted into the active detector volume, are

$$A_{\gamma_{\text{det},X_{1,16}}} = \frac{A_X}{4\pi d_{X_{1,16}}^2} \cdot A(06/2008) = 217 s^{-1} \quad (6.12)$$

$$A_{\gamma_{\text{det},Z_d}} = \frac{A_Z}{4\pi d_{Z_{\text{down}}}^2} \cdot A(06/2008) = 84 s^{-1} \quad (6.13)$$

$$A_{\gamma_{\text{det},Z_u}} = \frac{A_Z}{4\pi d_{Z_{\text{up}}}^2} \cdot A(06/2008) = 118 s^{-1} \quad (6.14)$$

The areas $A_X$ and $A_Z$ are the areas of the active detector volume given as

$$A_X = 2cm \cdot 5cm = 10 cm^2 \quad (6.15)$$
Chapter 6. Preliminary measurements

\[ A_Z = 0.32\, \text{cm} \cdot 5\, \text{cm} = 1.6\, \text{cm}^2 \]  

which signify the solid angle element the detector spans (since the source emits radiation into the whole \(4\pi\) solid angle).

Using the attenuation coefficient \(\mu\) of 1.25MeV \(\gamma\)'s (average energy of a \(\gamma\) particle from the \(^{60}\text{Co}\) source) in CS\(_2\) [62]

\[ \mu(1.25\, \text{MeV}) \simeq 5.70 \cdot 10^{-2}\, \text{cm}^2/\text{g} \]  

the mean free path of the \(\gamma\) particles in 80 and 120torr CS\(_2\) can be calculated as

\[ \lambda_{\gamma,80} = \frac{1}{\mu(1.25\, \text{MeV}) \cdot \rho_{80\text{CS}_2}} = 5.253 \cdot 10^{-4}\, \text{cm} \]  
\[ \lambda_{\gamma,120} = \frac{1}{\mu(1.25\, \text{MeV}) \cdot \rho_{120\text{CS}_2}} = 3.509 \cdot 10^{-4}\, \text{cm} \]  

The densities of CS\(_2\) at 80 and 120torr are \(3.334 \cdot 10^{-4}\, \text{g/cm}^3\) and \(5.000 \cdot 10^{-4}\, \text{g/cm}^3\) respectively.

Using all this information, the number of \(\gamma\)'s that will actually create tracks in the active detector volume in the X and Z directions is given as

\[ N_{\gamma_{\text{det}},80\, X,\, ^{60}\text{Co}} = \frac{l_{dx}}{\lambda_{\gamma,80}} \cdot A_{\gamma_{\text{det}},X1} \]  
\[ N_{\gamma_{\text{det}},80\, Z_{\text{down}},\, ^{60}\text{Co}} = \frac{l_{dz}}{\lambda_{\gamma,80}} \cdot A_{\gamma_{\text{det}},Z_{\text{down}}} \]  
\[ N_{\gamma_{\text{det}},120\, X,\, ^{60}\text{Co}} = \frac{l_{dx}}{\lambda_{\gamma,120}} \cdot A_{\gamma_{\text{det}},X1} \]  
\[ N_{\gamma_{\text{det}},120\, Z_{\text{down}},\, ^{60}\text{Co}} = \frac{l_{dz}}{\lambda_{\gamma,120}} \cdot A_{\gamma_{\text{det}},Z_{\text{down}}} \]  

In these equations, \(l_{dx}\) and \(l_{dz}\) are the distances that a \(\gamma\) particle can travel inside the CS\(_2\) and potentially create an electron track that will then be seen inside the active detector volume. \(l_{dx} = 25\, \text{cm}\) is chosen due to the larger distance electron tracks.
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will span in the gas and \( l_{dz} = 2cm \) is chosen, since electron tracks created above the cathode (or below the readout board) will not be able to go through the copper surfaces.

With these numbers, the expected numbers of \( \gamma \)'s to create a track in the active detector volume are

\[
N_{\gamma_{\text{det,}80X,60Co}} \simeq 372h^{-1} \quad (6.24)
\]
\[
N_{\gamma_{\text{det,}80Z\text{down},60Co}} \simeq 12h^{-1} \quad (6.25)
\]
\[
N_{\gamma_{\text{det,}120X,60Co}} \simeq 557h^{-1} \quad (6.26)
\]
\[
N_{\gamma_{\text{det,}120Z\text{down},60Co}} \simeq 17h^{-1} \quad (6.27)
\]

It can be seen that more \( \gamma \)'s are expected in the 120torr data and always a large factor more in the X directed data.

### 6.3.2 Comparing \(^{60}\text{Co}\) event rates

It has been shown above that the expected number of \( \gamma \) particles interacting in the active detector volume can be estimated. The actual, measured number of events was presented as well. These numbers can now be combined to give a detection efficiency that includes efficiencies of the detector, trigger efficiencies, dead-time efficiencies and cut efficiencies in the analysis. The results of the estimations and measurements are summarized in Table 6.2.

The number of total events seen in the table is lower than calculated by deviding the number of events after the analysis by the duration of the run seen in Table 6.1. The reason for this comes from the background run performed before taking data with the \(^{60}\text{Co}\) source. It yielded three events that passed the analysis cuts from above at a 200NIPs threshold. The run lasted 2.4h and therefore the background rate
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Table 6.2: Overview of the results of the $^{60}$Co run and the calculated, expected numbers of $\gamma$ events.

<table>
<thead>
<tr>
<th>Pressure (torr)</th>
<th>direction</th>
<th># of events (h$^{-1}$)(tot-bg)</th>
<th>Detection Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>X1 side</td>
<td>1.105</td>
<td>0.297 %</td>
</tr>
<tr>
<td>80</td>
<td>Z down</td>
<td>4.601</td>
<td>38.333 %</td>
</tr>
<tr>
<td>120</td>
<td>X1 side</td>
<td>2.136</td>
<td>0.383 %</td>
</tr>
<tr>
<td>120</td>
<td>Z down</td>
<td>1.042</td>
<td>6.129 %</td>
</tr>
<tr>
<td>Calculation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>X1 side</td>
<td>372</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>Z down</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>X1 side</td>
<td>557</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>Z down</td>
<td>17</td>
<td></td>
</tr>
</tbody>
</table>

at 80torr was 1.25 events per hour. This should be subtracted from the number of events per hour detected when running with the $^{60}$Co source. Since the background run was only performed for 80torr, the number of events collected in 120torr are not adjusted.

It can be seen in this Table that the detection efficiency is much better for the Z directed runs. It is also interesting to note that the detection efficiency for $\gamma$’s is better in the 80torr, Z directed data than the 120torr Z directed data. This is possibly due to the fact that the 120torr data was taken at lower gas gains. Low energy $\gamma$’s might have therefore not created enough charge to trigger readout.
Chapter 7

Measurements of nuclear recoil tracks using neutron exposures

The measurements performed to detect nuclear recoils in the detector are divided into two separate and very different methods. One measurement is performed with a deuterium-deuterium (DD) neutron generator and the second using a $^{252}$Cf radioactive source that produces neutrons via fission. The results of both of these measurements are discussed in the following chapter. It will be shown that nuclear recoils created by neutrons from the sources are seen in the detector and that there is little background contamination in the data. It will also be shown how well a directional signal can be reconstructed and the question of the head-tail asymmetry in the charge distribution is addressed. The size of this effect and its detectability and limitations due to the detector setup are discussed.
Chapter 7. Measurements of nuclear recoil tracks using neutron exposures

7.1 Setup and Run details

Neutron runs were conducted with the previously described prototype detector and setup in CS$_2$ at pressures of 40, 80 and 120torr. The neutrons in 40torr CS$_2$ were produced using a DD neutron generator on loan from D. Chichester of Idaho National Labs. The DD neutron generator creates monoenergetic neutrons of energy $E_{DD}=2.5\text{MeV} \pm 10\%$. How the neutron generator creates these neutrons is described in Appendix A.

The runs in 80 and 120torr CS$_2$ were performed using neutrons produced by a $^{252}$Cf source. The source produces neutrons through fission and they will therefore have a distribution of energies. Details of all three runs are discussed in the following two Sections.

7.1.1 40torr runs

The $^{252}$Cf source was not used to take data in 40torr. Instead all the 40 torr runs were performed with a DD neutron generator which delivered neutrons of an energy of $E_{DD}=2.5\text{MeV} \pm 10\%$. Data was taken over a period of 5 days due to the limited availability of the generator.

The DD generator was placed next to the vessel, in a spot that was chosen such that the neutrons will enter the active detector volume preferentially perpendicular to the X strips and parallel to the X-Y detector plane. This should therefore achieve nuclear recoils that will also be preferentially aligned perpendicular to the X strips and parallel to the X-Y detection plane. A schematic of this setup is shown in Figure 7.1.

The setup was not changed throughout the run, therefore only data from the strip 16X side exists for this run. This dramatically limits the information on the
Chapter 7. Measurements of nuclear recoil tracks using neutron exposures

Figure 7.1: Schematic of the setup of the DD generator with respect to the detector inside the vessel.

nuclear recoils that can be extracted. For example, no head-tail can be discussed, since it can only be assessed when data from both directions in X or Z is available. Since this data does not exist a statement about the head-tail effect can not be made. The same is true for directionality, which can not be assessed when no data in a different direction than X is available.

Another problem with the runs with the neutron generator was due to the trigger system. It was mentioned before, that the first trigger that was used, only had the capability to trigger on four strips in total. The problem with this was, that short tracks, which are mainly due to Sulfur recoils, were not recorded as often as long tracks. This creates an unbalance between the expected Carbon and Sulfur recoils and will allow for more Carbon to be detected.

Also, since the recoil tracks are generally longer in 40torr CS$_2$, a lot of the recoil tracks selected by the analysis will be high angle scatters, since they are mainly the recoils shorter than 3.2mm. This is especially true for Sulfur recoils.
Chapter 7. Measurements of nuclear recoil tracks using neutron exposures

Due to these reasons, the DD neutron generator data was not used in the following and results from the run are not presented.

7.1.2 80 and 120torr runs

As mentioned before, the $^{252}$Cf source used to create the nuclear recoils in the 80 and 120torr measurements will create neutrons with a distribution of energies. A measured energy spectrum for these neutrons is shown in Figure 7.2 [63].

The $^{252}$Cf source also produces $\gamma$ particles in the spontaneous fission process. It is found that there are approximately six $\gamma$’s for every neutron created in the process [61]. A spectrum of the $\gamma$’s is shown in Figure 7.3 [64] and it can be seen that the spectrum peaks at about 200keV.

The reason to study low energy nuclear recoils created from a $^{252}$Cf source and draw conclusions to WIMP detection is due to the similarity of the recoil spectra for the neutrons and the WIMPs in CS$_2$. This has been confirmed with a simulation by Snowden-Ifft [65]. The expected energy spectrum from recoils induced by the $^{252}$Cf compared to that of recoils induced by a 1000GeV WIMP is shown in Figure 7.4. The reason these spectra are only taken from neutron/WIMP Sulfur scattering is due to the fact that WIMPs will mainly scatter off Sulfur atoms.

Due to this similarity in the spectra, conclusions made from the neutron runs can be readily applied to draw conclusions from the neutron data to WIMP interactions in the detector.

The reason to do measurements at different pressures is simple. When increasing the pressure, the range of the recoiling nuclei decreases linearly. Since only 3.2mm in X and Y were implemented, higher pressure runs were used to allow for the measurement of higher energy nuclear recoils. Another option would have been to
implement more strips in X and Y, but this would have involved a more elaborate program that exceeded the time frame given for this project.

All the available data for the 80 and 120torr runs can be found in Appendix D in Table D.5.

The setup for the $^{252}$Cf neutron runs and their labels in the data files is shown in Figure 7.5.

The experimental setups for the X and Y directed runs shown in Figure 7.5 are shown from above, with the neutron source being represented as the gray square. The Z setup is shown schematically from the side.

Runs with the neutron source were performed in both X directions as well as both Z directions. It was decided not to take data in the Y direction though. The reason not to do this is due to the symmetry of the detector and it was assumed that the Y directed data would create the same results as the X directed data.

The neutron exposures with the $^{252}$Cf source were taken over long periods of time, lasting a few weeks each. During these long runs the gain was monitored with $^{55}$ calibration runs. The reason that the neutron exposures had to last so long is due to the very small size of the active detector volume. The expected interaction rate of neutrons in the detector is therefore estimated in the following section, Section 7.2. The total duration of each neutron run performed with the $^{252}$Cf source was as follows:

\[
\begin{align*}
\Delta t_{80\text{torr}, X\text{dir}} &= 106.767h \\
\Delta t_{80\text{torr}, Z\text{dir}} &= 40.533h \\
\Delta t_{120\text{torr}, X\text{dir}} &= 87.959h \\
\Delta t_{120\text{torr}, Z\text{dir}} &= 40.133h
\end{align*}
\]
Chapter 7. Measurements of nuclear recoil tracks using neutron exposures

The additional analysis procedures used in analyzing the neutron data is discussed in the following.

7.1.3 Additional analysis cuts for the neutron runs

When analyzing the data from the neutron runs, the following cuts were used in the secondary analysis (“ana.c”):

- **“total NIPs cut”**: This cut removes all tracks with charge less than a certain amount in NIPs. For this run, only events with \( q_{nips} > 500 \text{NIPs} \) were kept.

- **“containment cut”**: This cut removes all tracks that are not contained on the X strips. This means only events with \( q_i[0] < 30 \text{NIPs} \) and \( q_i[15] < 30 \text{NIPs} \) are kept using this cut. An example of a track removed by the “containment cut” is shown in Figure 7.6.

- **“broken-track cut”**: This cut removes all tracks that have strips with no charge inside a track. This cut was introduced when it was found that a fair amount of tracks would have strips with no charge in the middle of a track, e.g. strip 2, 3 and 4 were hit, 5 had no pulse, and 6, 7 and 8 were hit. When looking at these tracks it was clear that they comprised one single track, not two tracks coinciding in one event. Therefore, if a track would have more than one zero strip inside a track, the track was also removed by the analysis. A sample event that is removed by the “broken-track cut” is shown in Figure 7.7. This cut was introduced to remove gamma events, which have low dE/dx and often have strips with little or no ionization on them.

In the final stage of analysis, no additional cuts were performed. This stage of the analysis was only used to combine the various runs together and extract all the information.
Chapter 7. Measurements of nuclear recoil tracks using neutron exposures

7.2 Expected interaction rates of $^{252}$Cf neutrons in the detector

The expected interaction rates of the $^{252}$Cf neutrons in the active detector volume is discussed here. The activity of the $^{252}$Cf neutron source was about 0.251 mCi on 11/10/2007. When the runs were performed in March and April of 2008, the average activity of the source would have been

$$A_{March} = 0.230 mCi = 8.510 \cdot 10^6 \text{ decays/s} \quad (7.5)$$

$$A_{April} = 0.225 mCi = 8.325 \cdot 10^6 \text{ decays/s} \quad (7.6)$$

Since these numbers are similar, the average activity,

$$A_{\text{aver}} = 0.227 \text{ mCi} = 8.399 \cdot 10^6 \text{ decays/s},$$

will be used to determine the interaction rate of neutrons in the active detector volume.

Neutrons are emitted into the full solid angle of $4\pi$ with this activity. Since the width of the active detector volume in Y is about 5 cm along the X strips, the width in X is 3.2 mm along the Y strips and the height of the volume in Z is about 2 cm, the number of neutrons actually entering into this region, $N_{n_{\text{det}}}$, needs to be calculated. This will be a different number for X directed and Z directed runs.

For the X directed runs, the source is about $d_{sdX}=20$ cm away from the detector. The number of neutrons entering the active detector volume in an X directed run is therefore given as:

$$N_{n_{\text{det}},X} \approx A_{\text{aver}} \cdot \frac{0.02 m \cdot 0.05 m}{4\pi \cdot (0.2 m)^2} \approx A_{\text{aver}} \cdot 0.00199 \quad (7.7)$$

$$\approx 1.671 \cdot 10^4 \text{ neutrons/s} \quad (7.8)$$

For the Z directed runs, the source is about $d_{sdZ}=10$ cm away from the detector, but
Chapter 7. Measurements of nuclear recoil tracks using neutron exposures

the area they are emitted in is smaller. Therefore

\[
N_{n_{\text{det}},Z} \approx A_{\text{aver}} \cdot \frac{0.0032m \cdot 0.05m}{4\pi \cdot (0.1m)^2} \approx A_{\text{aver}} \cdot 0.00127 \tag{7.9}
\]
\[
\approx 1.069 \cdot 10^4 \text{neutrons/s} \tag{7.10}
\]

The interaction length of a neutron in 40torr CS\(_2\) can be calculated using the following equation from [66]

\[
l_{40,CS_2} = \frac{\rho \cdot N_A}{M} (n_1 \sigma_1 + n_2 \sigma_2) \tag{7.11}
\]

Here, \(\rho\) is the density of the gas \((\rho_{40,CS_2} = 1.667 \cdot 10^{-4} \text{g/cm}^3)\), \(N_A\) is Avogadro’s number \((6.022 \cdot 10^{23} \text{ mol}^{-1})\), \(M\) is the molecular weight of CS\(_2\) \((M_{CS_2} = 76 \text{ g/mol})\), \(n_i\) is the number of atoms of element \(i\) (C or S) in the molecule \((n_1 = n_C = 1\) and \(n_2 = n_S = 2\)) and \(\sigma_i\) is the total neutron cross section of the element \(i\).

The two neutron cross section for C and S are of course energy dependent, but since the energy spectrum of neutrons from the \(^{252}\text{Cf}\) source peaks at 1MeV, the cross sections can be chosen at 1MeV and it needs to be remembered that this is only a simplified assumption. The cross sections are taken from [67]. These can then be entered into Equation (7.11) and the interaction length is found to be

\[
l_{40\text{torr},1\text{MeV}} \approx 10^{-5} \text{cm}^{-1} \tag{7.12}
\]

It can be seen in Equation (7.11) that the interaction length scales linearly with pressure and therefore, the interaction lengths in 80 and 120torr of CS\(_2\) are given as:

\[
l_{80CS_2} \approx 2 \cdot 10^{-5} \text{cm}^{-1} \tag{7.13}
\]
\[
l_{120CS_2} \approx 3 \cdot 10^{-5} \text{cm}^{-1} \tag{7.14}
\]
Chapter 7. *Measurements of nuclear recoil tracks using neutron exposures*

Using all this information and knowing that the distance a neutron can scatter inside the detector volume is \(d_X = 3.2\,\text{mm}\) in the \(X\) directed runs and \(d_Z = 2\,\text{cm}\) in the \(Z\) directed runs, the expected interaction rates \(R_X\) and \(R_Z\) in 80 and 120torr can be calculated:

\[
R_{X,80} \approx A_{\text{det},X} \cdot d_X \cdot l_{80} \approx 0.107\,\text{s}^{-1} \approx 385\,\text{h}^{-1} \tag{7.15}
\]
\[
R_{Z,80} \approx A_{\text{det},Z} \cdot d_Z \cdot l_{80} \approx 0.428\,\text{s}^{-1} \approx 1541\,\text{h}^{-1} \tag{7.16}
\]
\[
R_{X,120} \approx A_{\text{det},X} \cdot d_X \cdot l_{120} \approx 0.161\,\text{s}^{-1} \approx 580\,\text{h}^{-1} \tag{7.17}
\]
\[
R_{Z,120} \approx A_{\text{det},Z} \cdot d_Z \cdot l_{120} \approx 0.642\,\text{s}^{-1} \approx 2311\,\text{h}^{-1} \tag{7.18}
\]

This shows two important things. The \(Z\) directed runs are expected to produce more recoils inside the active detector volume than the \(X\) directed runs and the interaction rate should be slightly higher for the runs in 120torr \(\text{CS}_2\). These interaction numbers are still very small though, considering that events might trigger the readout that are not or only semi-contained in the volume, therefore decreasing the number of expected events that will actually pass the analysis. This should give an indication already that the statistics of the neutron runs might be significantly limited.

### 7.3 Expected interaction rates of \(^{252}\text{Cf}\) \(\gamma\) particles in the detector

The expected interaction rates of \(\gamma\) particles created in the spontaneous fission process of the \(^{252}\text{Cf}\) source needs to be estimated as well. How this is done is shown in
Appendix 7.3. The resulting number of $\gamma$’s in each pressure and for X and Z directed data is summarized in the following.

\begin{align*}
N_{\text{exp}\gamma_{80 \text{X}, \text{noeff}}} &= 13840 \quad (7.19) \\
N_{\text{exp}\gamma_{80 \text{Z}, \text{noeff}}} &= 16014 \quad (7.20) \\
N_{\text{exp}\gamma_{120 \text{X}, \text{noeff}}} &= 17264 \quad (7.21) \\
N_{\text{exp}\gamma_{120 \text{Z}, \text{noeff}}} &= 22815 \quad (7.22)
\end{align*}

7.4 Background and $\gamma$ particle rejection

It is important to know if there are any background or $\gamma$ particle events in the data and if it is possible to separate them from the neutron events. It has been shown in Section 6.3, that a range versus NIPs plot is a powerful tool to identify a $\gamma$ event from a neutron event. It has been seen in that section, that most of the $\gamma$ events collected are in the low NIPs and high range region. It needs to be seen where the neutron events are positioned in such a plot.

The range of a nuclear recoil track is usually defined in a three dimensional way as:

\[ R := \sqrt{\Delta X^2 + \Delta Y^2 + \Delta Z^2} \quad (7.23) \]

$\Delta X$, $\Delta Y$ and $\Delta Z$ are the lengths of a given track in the X, Y and Z direction.

Due to the small size of the active detector volume, the trigger system as discussed in Section 3.5 was only set up to trigger on events on the X strips. If the trigger of the Y strips would have been implemented, the active detector volume would have
been reduced from 3.2mm x 5cm x 2cm to only 3.2mm x 3.2mm x 2cm. Considering
the expected, already low interaction rates for the larger detector volume, including
the Y strips would have furthermore decreased the available data. It was therefore
decided that only tracks on the X strips would trigger a data readout from the WFDs.
The Y strips were still readout and, if by coincidence a track did extend onto the Y
strips, their information was also analyzed.

Due to the lack of information in the Y direction, only the two dimensional range
can be considered. This range R2 is defined as

\[ R_2 := \sqrt{\Delta X^2 + \Delta Z^2} \]  

(7.24)

As in the 3D range, \( \Delta X = \text{track} \rightarrow x \) and \( \Delta Z = \text{track} \rightarrow Dzp \).

The total charge or energy of a recoil event is given as \( Q(\text{NIPs}) = \text{track} \rightarrow q\text{nips} \),
which is defined in Chapter 4.

Using the two dimensional range defined in Equation 7.24 and the total charge in
NIPs of an event, the 2D range versus NIPs plot from the 80torr, X directed neutron
run is shown in Figure 7.8. The corresponding plots for the Z directed run in 80torr
and the X and Z directed runs in 120torr can be found in Appendix C

Two bands can easily be identified in this plot. One of the bands is the one on the
left side of the plot which is almost parallel to the R2 axis. The second band extends
farther to the right and has shorter ranges at higher energies. These two bands can
be identified by comparing them to the R2 versus NIPs plots of the \( \gamma \) events in the
\( ^{60}\text{Co} \) run. The R2 versus NIPs plot from the X directed \( ^{60}\text{Co} \) run in 80torr \( \text{CS}_2 \) is
plotted in the same plot with the X directed neutron run in 80torr, which is shown
in Figure 7.9

It can be seen in this plot that the \( \gamma \) events from the \( ^{60}\text{Co} \) run overlap with the
vertical band described above. This means, removing this band from the data will
Chapter 7. Measurements of nuclear recoil tracks using neutron exposures

then only leave the neutron events in the second band.

The \( \gamma \) band can be removed from the data by drawing a line to separate the two and any event with range and energy below the line is accepted as a neutron event. This method is shown in Figure 7.10.

The function used to remove the \( \gamma \) events from the neutron data is

\[
f_{80X}(E) = 1.218 \cdot 10^{-3} \cdot E(NIPs) + 0.8329
\]

The functions used to remove the \( \gamma \) events from the neutron data in the Z direction in 80torr CS\(_2\) and the X and Z directions in 120torr are as follows:

\[
f_{80Z}(E) = 0.9670 \cdot 10^{-3} \cdot E(NIPs) + 0.6350
\]

\[
f_{120X}(E) = 0.8219 \cdot 10^{-3} \cdot E(NIPs) + 0.2215
\]

\[
f_{120Z}(E) = 0.8798 \cdot 10^{-3} \cdot E(NIPs) + 0.2212
\]

The number of \( \gamma \) events removed from the neutron data can be compared to the expected amount of \( \gamma \)'s calculated in Section 7.3. The detection efficiency for \( \gamma \) particles in the neutron data can also be calculated and can be compared to the detection efficiency of \( \gamma \)'s from the \( ^{60}\text{Co} \) source. All this information is summarized in Table 7.1 for the four different neutron runs performed.

It can be seen in this table that the detection efficiencies of \( \gamma \)'s is slightly larger for the runs with the \(^{252}\text{Cf} \) source in the 120torr, X and Z directed runs and the 80torr X directed run. The detection efficiency for the Z directed run in 80torr is much smaller for the run with the \(^{252}\text{Cf} \) source than it is with the \(^{60}\text{Co} \) source. The reasons for this could be varied. The most likely reason for this difference lies in the fact that the discriminator threshold of the trigger system was not set at exactly the same level for the runs with the neutron source as it was with the \( \gamma \) source.

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Table 7.1: Summary of the results of the $\gamma$ particle measurements with the $^{252}$Cf and $^{60}$Co sources and the calculations of expected number of events in the data.

<table>
<thead>
<tr>
<th>P(torr) &amp; direction</th>
<th>Events in data</th>
<th>Expected events</th>
<th>Detection Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>252Cf source</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>80,X</td>
<td>362</td>
<td>13840</td>
<td>2.616 %</td>
</tr>
<tr>
<td>80,Z</td>
<td>96</td>
<td>16014</td>
<td>0.599 %</td>
</tr>
<tr>
<td>120,X</td>
<td>488</td>
<td>17264</td>
<td>2.827 %</td>
</tr>
<tr>
<td>120,Z</td>
<td>1981</td>
<td>22815</td>
<td>8.683 %</td>
</tr>
<tr>
<td>60Co source</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>80,X</td>
<td>34</td>
<td>11470</td>
<td>0.296 %</td>
</tr>
<tr>
<td>80,Z</td>
<td>291</td>
<td>759</td>
<td>38.340 %</td>
</tr>
<tr>
<td>120,X</td>
<td>43</td>
<td>11214</td>
<td>0.383 %</td>
</tr>
<tr>
<td>120,Z</td>
<td>23</td>
<td>375</td>
<td>6.133 %</td>
</tr>
</tbody>
</table>

This leads to the different detection efficiencies for the $\gamma$’s in the runs with the two different sources.

The results presented give confidence that the $\gamma$ events can be removed from the neutron data very efficiently down to an energy of 200NIPs. Removing the $\gamma$ band from the neutron data leaves a certain number of nuclear recoils in the data which is summarized in Table 7.2.

Table 7.2: Number of nuclear recoil events left in the data after removing the $\gamma$ band compared to the expected number of neutron events calculated in Section 7.2.

<table>
<thead>
<tr>
<th>252Cf source</th>
<th>P(torr) &amp; direction</th>
<th>Events in $^{252}$Cf data</th>
<th>Expected events</th>
<th>Detection Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>80,X</td>
<td>449</td>
<td>41140</td>
<td>1.091 %</td>
</tr>
<tr>
<td></td>
<td>80,Z</td>
<td>827</td>
<td>62453</td>
<td>1.324 %</td>
</tr>
<tr>
<td></td>
<td>120,X</td>
<td>944</td>
<td>50981</td>
<td>1.852 %</td>
</tr>
<tr>
<td></td>
<td>120,Z</td>
<td>1797</td>
<td>92755</td>
<td>1.937 %</td>
</tr>
</tbody>
</table>
Chapter 7. Measurements of nuclear recoil tracks using neutron exposures

Table 7.3: Summarizing the number of events in the background runs when no source was present.

<table>
<thead>
<tr>
<th>P(torr)</th>
<th>total Events</th>
<th>Events after Background events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>data</td>
<td>ana (&gt; 200NIPs)</td>
</tr>
<tr>
<td>80</td>
<td>91</td>
<td>6</td>
</tr>
<tr>
<td>120</td>
<td>412</td>
<td>72</td>
</tr>
</tbody>
</table>

It can be seen in the table that the detection rates for neutrons is not very high, which was expected. Since a lot of events will have an extent in X much larger than the 3.2mm available, a lot of the events are removed with the containment cut. Furthermore, the dead time of the readout system was much larger than the trigger rate and many neutron events were therefore not even written to file. It is important to note though that the detection efficiencies for the different runs are very similar.

Background runs were performed as well. These were taken with the neutron source safely stored away, so that there would not be any residual radiation from the source contaminating the background. The available background data is shown in Table D.2 in Appendix D. Running the same analysis with the same cuts introduced above, yields a certain amount of events per hour. The results are summarized in Table 7.3.

When plotting the background events that were observed in an R2 versus NIPs plot, they can also be found in the region of the γ band. It can therefore be concluded that there is minimal contamination of the neutron data with background events.

### 7.5 Discrimination of Carbon and Sulfur events

When a WIMP interacts in a detector filled with gaseous CS$_2$, it is far more likely to interact with the Sulfur atoms than the Carbon atoms. The reason for this was
Chapter 7. Measurements of nuclear recoil tracks using neutron exposures

mentioned in Section 1.3.1 and is due to the linear dependence of the WIMP-nucleon scattering cross section on the mass of the target nucleus. Due to this peculiarity of the WIMP interactions, it would be helpful to identify any interactions in the detector as Carbon and Sulfur recoils. This way, any conclusions drawn from the measurements of the directionality and the head-tail effect can be attributed to the recoils of interest, which are the Sulfur recoils. Any measured characteristic of Carbon recoils is not of any interest since they will not be primarily created by the WIMP interactions.

To distinguish between Carbon and Sulfur recoils in the detector, the range of a recoil at a certain energy in NIPs needs to be investigated. It has been shown in [32] and in even more detail in [54], that Carbon recoils are expected to have a much longer range for a given energy than Sulfur recoils. This has been shown in measurements as well as Monte-Carlo simulations [54]. In general, the reason for the Sulfur recoils to be shorter than the Carbon recoils at the same energies, is due to the fact that their velocity is less than that of Carbon recoils From kinetic considerations the Sulfur recoils will have to create shorter tracks. Due to the Carbon atoms being lighter and therefore having a larger velocity component at the same energies, their tracks are expected to be longer. The result of this is, that when plotting the range versus energy for Carbon and Sulfur events, the Carbon events should be separate from the Sulfur events. It needs to be investigated if this effect is large enough that it can be observed and if a separation is seen between the two, how well can it be resolved.

It has been mentioned before, Equation 7.23, that the range of a nuclear recoil track is usually defined in a three dimensional way:

$$ R := \sqrt{\Delta X^2 + \Delta Y^2 + \Delta Z^2} \quad (7.29) $$

It was also mentioned that, due to the setup of the trigger, information of the tracks
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in the Y direction was lacking. Therefore, only the two dimensional range was considered (see also Equation 7.24):

\[ R^2 := \sqrt{\Delta X^2 + \Delta Z^2} \] (7.30)

In this equation, \( \Delta X = \text{track} \rightarrow x \) and \( \Delta Z = \text{track} \rightarrow Dzp \). The total charge or energy of a recoil event is given as \( Q(\text{NIPs}) = \text{track} \rightarrow q\text{nips} \), which is defined in Chapter 4.

For the different available runs, the 2D range can be plotted versus the total charge of a track and compared to the results found by Snowden-Ifft in [32]. A table summarizing his findings is shown in Figure 7.11.

For the different available runs, the 2D range can be plotted versus the total charge of a track and compared to the results found by Snowden-Ifft in [32]. A table summarizing his findings is shown in Figure 7.11.

This table summarizes results for nuclear recoil tracks in 40torr of CS\(_2\) and the ranges given in it are three dimensional. When investigating tracks in 80torr and 120torr, the ranges will scale linearly with pressure. This means, the range of a track in 80torr is found by dividing the 3D range in the table of Figure 7.11 by a factor of two. For example a 1000NIPs Sulfur recoil, which has a range of 0.858mm in 40torr will have a range of 0.858mm/2 = 0.429mm in 80torr CS\(_2\). Similarly in 120torr, the range would be divided by a factor of three, which means a 1000NIPs Sulfur recoil in 120torr would have a range of \( R^2 = 0.858\text{mm}/3 = 0.286\text{mm} \). Since the ranges in the table are three dimensional, the measured ranges are expected to be smaller. It should be mentioned here as well, that there is a significant uncertainty to the measured ranges summarized in this table. Since DRIFT has 2mm wire spacings, the extent of the track in X strongly depends on the way \( \Delta X \) is defined in the data. An uncertainty of 1mm associated with the measurement of \( \Delta X \) is not unreasonable (see [54]). Furthermore, the extent of the track in Z is overestimated. \( \Delta Z \) is calculated
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as the width of a pulse from start to end time (time when the pulse crosses zero) multiplied by the drift velocity. Due to the inherent shape of a pulse defined by the shaping and amplifying electronics, this will give a larger value for $\Delta Z$ than if it was measured independently. Therefore, any kind of systematic shift in the measured range compared with the ranges presented in Figure 7.11 might be due to these uncertainties.

When scaling the findings in Figure 7.11 to the right pressures, the charge of a track in NIPs will scale to the recoil energy the same way in 40, 80 and 120torr.

The 2D range for the X directed and Z directed runs in 80torr can be plotted versus the recoil energy in NIPs. They are plotted separately to ensure any differences in the runs can be taken into account when evaluating these plots.

The cuts used in the primary analysis of the 80torr and 120torr data are the same as introduced in Section 7.1.2. In addition to these cuts, for the X directed runs only events with $\text{track} \rightarrow DZ < 1.0\text{mm}$ were combined in the final analysis. Using this cut, events with a large $\Delta Z$ component are removed. The reason to do this, is that this way it is ensured that only tracks are considered that are relatively parallel to the X-Y detector plane. Similarly, in the Z directed runs only events with $\text{track} \rightarrow x < 1.5\text{mm}$ were combined in the final analysis. This removes tracks with a large $\Delta X$ component and ensures that the tracks are mostly parallel to the X-Z detector plane.

The 2D range versus NIPs plot for X directed neutron run with the $\gamma$ band removed is shown in Figure 7.12. The scaled R versus NIPs values from the table in Figure 7.11 are plotted as well to show the optimal position of the Carbon and Sulfur bands. Similar plots for the Z directed run in 80torr and the X and Z directed runs in 120torr can be found in Appendix C as well.

It can be seen in this plot, that a separation of the Carbon and Sulfur bands is
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not observed. If there are indeed both kinds of recoils in the data, they can not be easily identified.

A simulation of the Carbon and Sulfur recoils has been performed using a simulation code by D. Snowden-Ifft. It was found, that in a simulation that does not include efficiencies of the detector such as size of the active detector volume, approximately $2^{-} = 30\%$ of the events in the neutron band will be due to Carbon recoils. Since no cuts have been performed on the neutron band, this will be the largest number of Carbons in the data. It is expected though, that geometrical considerations of the detector would decrease this fraction, since the Carbon recoils are longer in general and are therefore more likely to extend outside of the 3.2mm of implemented strips in X. Any conclusion that will be made about the directionality of the detector and the ability to measure the head-tail effect, are therefore applicable to a mixture of Carbon and Sulfur recoils.
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Figure 7.2: Energy spectrum of $^{252}$Cf fission neutrons [63]. The spectrum drops rapidly above an energy of 1.0 MeV.
Figure 7.3: Energy spectrum of $\gamma$ particles created in the spontaneous fission process of $^{252}$Cf [64]. It peaks at a $\gamma$ energy of about 200keV.
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Figure 7.4: Expected energy spectrum of sulfur recoils produced in 40torr CS$_2$ by $^{252}$Cf neutrons on the left and by 1000GeV WIMPs on the right side [63].
Figure 7.5: The different positions of the $^{252}$Cf source with respect to the detector and how the runs are labeled is shown here. Not all of the Y configurations were used in the data taking which can be seen from the neutron file list in the Appendix. The position “x16” is also referred to as “neutron unpleasant x” and position “x1” as “neutron pleasant x”.
Figure 7.6: Sample event from a $^{252}$Cf run that is removed by the “containment cut”.
Figure 7.7: Sample event from a $^{252}\text{Cf}$ run that is removed by the “broken-track cut”.
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Figure 7.8: Two dimensional range versus Energy in NIPs plot from 80torr, X directed neutron run with the $^{252}$Cf source. The energy is plotted from 200NIPs to 10000NIPs. Two bands can be seen in the plot, one is due to the neutrons (going towards the right, shorter ranges at higher energies) and the other is due to $\gamma$ particles (on the left, longer ranges at smaller energy)
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Figure 7.9: Two dimensional range versus NIPs plot from the X directed 80torr run overlaid with the X directed $^{60}$Co run in 80torr CS$_2$. The blue points correspond to events from the neutron run and the red points are the data points from the $\gamma$ events in the $^{60}$Co run.
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Figure 7.10: Two dimensional range versus NIPs plot from the X directed 80torr run showing the line that is used to remove the $\gamma$ events from the neutron data.
Figure 7.11: This table summarizes the findings of Snowden-Ifft in [32] and [54]. It shows the relationship between three dimensional track range (R3) and NIPs and also gives the conversion from charge in NIPs to recoil energy in keV.

<table>
<thead>
<tr>
<th>NIPs</th>
<th>S Energy (keV)</th>
<th>S Range (mm)</th>
<th>C Energy (keV)</th>
<th>C Range (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>26.8</td>
<td>0.487</td>
<td>16.7</td>
<td>1.67</td>
</tr>
<tr>
<td>1000</td>
<td>47.2</td>
<td>0.858</td>
<td>30.9</td>
<td>3.09</td>
</tr>
<tr>
<td>1500</td>
<td>64.6</td>
<td>1.17</td>
<td>41.8</td>
<td>4.17</td>
</tr>
<tr>
<td>2000</td>
<td>81.9</td>
<td>1.49</td>
<td>53.5</td>
<td>5.34</td>
</tr>
<tr>
<td>3000</td>
<td>115</td>
<td>2.10</td>
<td>83.8</td>
<td>8.37</td>
</tr>
<tr>
<td>4000</td>
<td>150</td>
<td>2.72</td>
<td>114</td>
<td>11.4</td>
</tr>
<tr>
<td>5000</td>
<td>184</td>
<td>3.34</td>
<td>144</td>
<td>14.4</td>
</tr>
<tr>
<td>6000</td>
<td>218</td>
<td>3.96</td>
<td>175</td>
<td>17.4</td>
</tr>
<tr>
<td>7000</td>
<td>252</td>
<td>4.58</td>
<td>205</td>
<td>20.5</td>
</tr>
<tr>
<td>8000</td>
<td>286</td>
<td>5.20</td>
<td>235</td>
<td>23.5</td>
</tr>
<tr>
<td>9000</td>
<td>320</td>
<td>5.82</td>
<td>266</td>
<td>26.5</td>
</tr>
<tr>
<td>10000</td>
<td>354</td>
<td>6.43</td>
<td>296</td>
<td>29.5</td>
</tr>
</tbody>
</table>
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Figure 7.12: Two dimensional range versus Energy in NIPs plot from X directed run in 80torr CS$_2$ compared with the expected R2 versus NIPs plot for Carbon and Sulfur recoils.
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7.6 Directionality of the Prototype Detector

Since the goal of the measurements with the prototype detector is to explore if 3D vector tracking of WIMP induced Sulfur recoils is possible, it needs to be shown that the detector is indeed directional and how well direction can be reconstructed. To achieve this, the two neutron exposures in the X1 and X16 direction are combined to one X directed run and the Zup and Zdown runs are combined to one Z directed run. In the following, they will be referred to as the X directed and Z directed data in 80 and 120torr.

It is expected that the X directed runs would have larger components of $\Delta X$ (range in X) than the Z directed runs. The same is true for $\Delta Z$, which is expected to be larger for Z directed runs than for X directed runs. Combining these two variables, the “angle” $\Delta Z/\Delta X$ can be defined as a more powerful variable. This should be larger for Z directed runs and smaller for X directed runs. If Y directed runs were available, their $\Delta Z/\Delta X$ should be in between the two.

7.6.1 Measurement of $\Delta X$

The extent of a track in X is measured as the number of strips with pulses with a charge greater than 5NIPs, multiplied by the strip pitch of 200$\mu$m:

$$\Delta X = \text{track} \rightarrow x = \# \text{strips hit} \cdot 0.2\text{mm}$$

The extent of a track in X can be histogrammed for different energy bins for the X and the Z directed runs in 80 and 120torr. Each histogram was fitted by a Gaussian and the $\mu$ and $\sigma$ of this fit were recorded. The various distributions of $\Delta X$, with the Gaussian fit, are shown for each energy bin in the X and Z directed data in Appendix C. For each energy bin, the mean of the $\Delta X$ distribution is plotted separately for X
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and Z directed.

The available statistics to perform this analysis are shown in Figure 7.13 for the 80 and 120torr runs.

![Graph](image)

Figure 7.13: Number of events in each NIPs bin for X directed (green) and Z directed (blue) runs in 80torr on the left and 120torr on the right. The energy bins are from 500 to 1000NIPs and then in steps of 1000NIPs.

It can be seen that there are more events available in the 120torr run. Both Z directed runs have higher statistics as well. Especially the first energy bin from 500 to 1000NIPs in the 80torr data has very low statistics compared to the next bin. The first bin in the 80torr data should therefore be taken with caution.

For 80torr, the distributions of $\Delta X$ in the X and Z directed runs in 80torr are shown in Figure 7.14.

![Graph](image)

The two distributions of $\Delta X$ are only clearly resolved for energies larger than 5000NIPs. For lower energies than that, the separation is not as clear. It is important to see though, that the $\Delta X$ value for the X directed runs is consistently larger than the one from the Z directed runs. This was expected and it is good to see this confirmed in the data.

To gauge the significance of this result, the events needed for a $2\sigma$ separation of
Figure 7.14: $\Delta X$ from 80 torr, X directed runs in red and from Z directed runs in green. A clear difference of the two can be seen from about 5000NIPs onwards. The separation of the two $\Delta X$ distributions is not as clear for energies below 5000NIPs, but the extent of $\Delta X$ for the X directed data is consistently larger than the one from the Z directed data, as was expected.

The distributions can be computed using:

$$N_{2\sigma} = 4 \cdot \frac{\sigma_X^2 + \sigma_Z^2}{(\mu_X - \mu_Z)^2}$$

(7.32)

This value can be calculated for each energy bin and is shown for the 80torr data in Figure 7.15.

It can be seen here that the number of events needed for the $2\sigma$ separation of the distributions are very small above 5000NIPs and on the order of a couple hundred events before that. The error bars on this plot were computed through
Figure 7.15: Number of events needed in each energy bin to achieve a $2\sigma$ separation of the two $\Delta X$ distributions in 80torr.

The same analysis is performed on the 120torr data. The two distributions of $\Delta X$ for the X and Z directed runs are shown in Figure 7.16.

It can be seen in this plot, that the two $\Delta X$ distributions change between energy bins. Sometimes the X directed $\Delta X$ is larger than the Z directed one and sometimes the opposite is true. This is not a good behavior to observe, since this means that no statement can be made about the number of events needed to separate the two distributions, since they are not supposed to separate with the $\Delta X_Z$ being larger. This is the reason the plot showing the number of events needed to see a $2\sigma$ separation of the two distributions is not shown. It could have been plotted for energies larger...
Figure 7.16: $\Delta X$ from 120torr X directed runs in red and from Z directed runs in green. A clear difference of the two can be seen from about 5000NIPs onwards. Before the 5000NIPs bin, the two signatures can be seen to oscillate, indicating that $\Delta X$ might not be a good directionality parameter to use in 120torr.

There are various reasons that can explain the behavior of the $\Delta X$ component. First of all, the Z directed runs were not really aligned perfectly parallel to the Z axis. Due to the small extent of the detector in X, it is very likely that the source was placed somewhat off axis. This means that the Z directed events will have larger X components than they would if the source was aligned perfectly. When combining...
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this with the short track lengths at low energies, a separation of the X and Z directed data using $\Delta X$ will be hard, since the detector can not resolve these small tracks. Taking a look at the table in Figure 7.11, shows that in 120torr, the track lengths are expected to be

\begin{align*}
R_{2120}(500\text{NIPS}) &= 0.162\text{mm} \\
R_{2120}(1000\text{NIPS}) &= 0.286\text{mm} \\
R_{2120}(5500\text{NIPS}) &= 0.39\text{mm} \\
R_{2120}(2000\text{NIPS}) &= 0.497\text{mm} \\
R_{2120}(3000\text{NIPS}) &= 0.700\text{mm}
\end{align*}

(7.33) (7.34) (7.35) (7.36) (7.37) (7.38)

These are all one or two strip hits and would be for the Z directed runs as well. This means the detector can not resolve the subtle differences in these short track. It would have been interesting to have a comparison with 40torr data, since the tracks are expected to be twice as long as the 80torr tracks there.
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7.6.2 Measurement of $\Delta Z$

Substantially different from the $\Delta X$ measurement, the $\Delta Z$ directionality is calculated using the time information. As discussed in Chapter 4, the extent of a track in $Z$ is calculated as

$$track \to Z = (t_{l,h} - t_{f,h}) \cdot v_{Drift}$$  \hspace{1cm} (7.39)

How these times are defined has been discussed in Section 4.1.1. This was chosen as a good measure of $\Delta Z$, since the half time of the pulse can be thought of as the center of a charge distribution in the $Z$ direction that reaches a given strip.

As shown in the previous section for $\Delta X$, $\Delta Z$ can be histogrammed for different energy bins and these histograms are then fit by a Gaussian. The mean $\mu$ and the standard deviation $\sigma$ of the Gaussian are recorded and the mean is plotted separately for $X$ and $Z$ directed runs. The histograms for the various energy bins with the fitted Gaussian are shown in Appendix E.

Since there are no additional cuts performed on the data to extract $\Delta X$ and $\Delta Z$, the available events are the same for the $\Delta Z$ distributions as was shown for the $\Delta X$ distributions in Figure 7.13.

For the 80torr run, the plot of the means of the $\Delta Z$ distributions is shown in Figure 7.17.

The two distributions for $\Delta Z$ can be seen separated at about 4000 NIPs. This is much better than the result from the $\Delta X$ measurement. As was expected, the length in $Z$ is longer for $Z$ directed runs.

To see the significance of this result, a plot of the events needed for a $2\sigma$ separation of the two distributions is created according to Equation(Equ2sigNev). This is shown in Figure 7.18.
Figure 7.17: $\Delta Z$ in 80torr from Z directed run in red and from X directed run in green for 80torr runs. A clear difference of the two can be seen from about 4000NIPs onwards.

It can be seen here that the numbers for the 1500 and 3500NIPs bins are missing. This is because the numbers are greater than 5000 events. It can therefore be said that for an energy larger than 4000NIPs, $\Delta Z$ will become a valuable indicator for the direction of a recoil. It is above 5000NIPs though that $\Delta Z$ becomes an excellent indicator for direction in 80torr of CS$_2$.

The same procedure is now repeated for the 120torr runs. The distributions of the means for X and Z directed runs in 120torr are shown in Figure 7.19.

The difference in the distributions of $\Delta Z$ can be seen at about 2000NIPs, which is very good when compared to the higher energy threshold for separation in the $\Delta X$ results. This is very low energy, especially when taking into consideration that these
tracks are very short in 120torr of CS$_2$. It seems that $\Delta Z$ is a very good variable to use for determining direction.

To show how significant this result really is, the number of events needed for a $2\sigma$ separation of the two distributions is calculated again. A plot of this is shown in Figure 7.20.

For all the energy bins but the 1000 to 2000NIPs bin, the events needed for a $2\sigma$ separation are below 100 events. This is a great result, especially for this high pressure and the discouraging result in 80torr.

The reasons that the $\Delta Z$ directionality is worse for the 80torr runs could be var-

Figure 7.18: Number of events needed in each energy bin to achieve a $2\sigma$ separation of the two $\Delta Z$ distributions in 80torr. The number of events for the 1500NIPs and 3500NIPs bin are both larger than 5000.
Figure 7.19: Distributions of $\Delta Z$ in 120torr from Z directed runs in red and from X directed run in green. A clear difference of the two can be seen from about 2000NIPs onwards. The separation of the two distributions looks a lot better than the one from 80torr.

ied. Since the 80torr and 120torr runs were taken at different times, the positions of the source in the Z directed runs could have changed. Since only 3.2mm in X were implemented it was very hard to align the source exactly above the X strips, which would have created perfectly aligned Z directed runs. It was already mentioned in the $\Delta X$ section, that the scenario is more likely where the source was a little off to the side, therefore creating recoils that would not be pointing straight down but would be along an angle. If now this offset was much larger for the 80torr runs, the difference in $\Delta Z$ for X and Z directed runs would be smaller than for the case were the source is more central to the X strips. One way to get around this problem is to look at a combined variable, $\Delta X/\Delta Z$, which might give a way to get around this
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Figure 7.20: Number of events needed in each energy bin to achieve a 2\(\sigma\) separation of the two \(\Delta Z\) distributions in 120torr.

problem in 80torr (and the \(\Delta X\) problem in 80torr).

7.6.3 Measurement of \(\Delta Z/\Delta X\)

To resolve the issues that were seen with the \(\Delta X\) measurement in 120torr and the \(\Delta Z\) measurement in 80torr, a new variable can be introduced, which is related to
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the angle between the Z and X components. This variable is defined as

\[ \phi = \frac{\Delta Z}{\Delta X} \]  

(7.40)

This variable is expected to be larger for Z directed runs and smaller for X directed runs.

Since this is a combination of the two directional signatures, this might give an even larger effect than the two signatures alone, such that less events would be needed to resolve the direction of the incoming particle. It is also possible that this variable will remove the problems seen with the single distributions and that it will be possible to simply use \( \phi \) for directionality.

As has been done separately for the two signatures in the previous sections, the fraction \( \Delta Z/\Delta X \) of each event can be histogrammed for each energy bin and the mean and RMS plotted for the X and Z directed runs separately. The histograms of \( \Delta Z/\Delta X \) for each energy bin can be found in Figures E.5, E.6, E.11 and E.12 in Appendix E.

In 80 torr, recording the means and standard deviations of these distributions and plotting them for each energy bin is shown in Figure 7.21.

The two distributions of \( \Delta Z/\Delta X \) in 80torr are well separated above 3000NIPs. The separation is also consistent throughout, meaning the signature of \( \Delta Z/\Delta X \) is always larger for Z directed runs as was expected. There is a slight dip in the Z directed data at 8500NIPs. This is attributed to the low statistics at the higher energy bins, which will negatively affect the fitting of the histogram.

The significance of the result can again be gauged by looking at the events needed to get a 2\( \sigma \) separation between the two distributions. This is shown for the \( \Delta Z/\Delta X \) signature in 80torr in Figure 7.22.
Figure 7.21: Distributions of $\Delta Z/\Delta X$ in 80torr from Z directed runs in red and from X directed runs in green in 80torr. A clear difference of the two can be seen from about 3000NIPs onwards. This is similar to the effect that was seen from the $\Delta Z$ measurement alone.

This result is better than the result from $\Delta Z$ in 80torr and improves the result from $\Delta X$ in the sense that now the number of events needed are decreasing the larger the energy, which is an effect that is expected.

Repeating this analysis for 120torr, the two distributions of $\phi$ are shown in Figure 7.23.

A separation of the two distributions can be observed from about 2000NIPs onwards. This is similar to the result from the $\Delta Z$ distributions alone in 120torr. The curves are very well separated, especially for energies greater than 5000NIPs. As was expected, the distribution for the Z directed runs (red) lies above the distribution
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Figure 7.22: Number of events needed in each energy bin to achieve a $2\sigma$ separation of the two $\Delta Z/\Delta X$ distributions in 80torr.

for $X$ directed runs (green).

The number of events needed to get a $2\sigma$ separation between the two distributions are also plotted again, shown in Figure 7.24.
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Figure 7.23: Distributions of $\Delta Z/\Delta X$ in 120torr from Z directed run in red and from X directed run in green. A clear difference of the two can be seen from about 2000NIPs onwards. This is similar to the effect that was seen from the $\Delta Z$ measurement alone.
Figure 7.24: Number of events needed in each energy bin to achieve a $2\sigma$ separation of the two $\Delta Z/\Delta X$ distributions in 120torr.
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As was seen in the $\Delta Z$ distributions, in all but one energy bin are the events needed less than one hundred. This is remarkable for this high pressure when the tracks are so incredibly short at low energies.

It is curious to note though, that the 120torr runs seem to give better results than the 80torr runs. One of the reasons for this has already been discussed and is related to source alignment. Another reason could be that it was observed throughout the 80torr runs, that the noise in the system was much larger. This was possibly due to noise on the power lines, but was not investigated in more detail during the run.

To summarize these results, the values plotted above for the needed events in each energy bin are summarized in Table(summarize). Since an actual WIMP interacting in the detector would transfer different amounts of energy to a nucleus in the scattering event, it is useful to combine the presented results above and find out how many events would be needed in the energy bin from 500NIPs to 5000NIPs so it can be said with 90% confidence that the neutron (or WIMP) came from a certain direction (if that direction is aligned with the X or Z axis). A statement can not be made at this point about events that enter the detector in random directions.

The significance $S$ of the result is calculated as

$$ S = \frac{\mu_X - \mu_Z}{\sqrt{\frac{\sigma_X^2}{N_X} + \frac{\sigma_Z^2}{N_Z}}} \quad (7.41) $$

In this expression $\mu_X$ and $\mu_Z$ are the means of the distributions of $\Delta X$, $\Delta Z$ or $\Delta Z/\Delta X$ in the X and Z directions respectively. The $\sigma$’s are the standard deviations and $N_X$ and $N_Z$ are the available events in the X and Z directed runs.

To calculate the number of events needed along each axis to achieve a 90% confidence level, one can use Equation (7.41), set $N_X = N_Z = N$ and solve for N. This
Chapter 7. Measurements of nuclear recoil tracks using neutron exposures

Table 7.4: Events needed to know the direction of an incident WIMP or neutron with 90% confidence.

<table>
<thead>
<tr>
<th>P(torr),Direction</th>
<th>$\mu X$</th>
<th># Evs</th>
<th>S</th>
<th># evs for 90% conf.</th>
</tr>
</thead>
<tbody>
<tr>
<td>80, Xdir</td>
<td>1.092 ± 0.024</td>
<td>328</td>
<td>4.95</td>
<td>44</td>
</tr>
<tr>
<td>80, Zdir</td>
<td>0.952 ± 0.015</td>
<td>517</td>
<td>4.95</td>
<td>44</td>
</tr>
<tr>
<td>120, Xdir</td>
<td>0.608 ± 0.010</td>
<td>454</td>
<td></td>
<td></td>
</tr>
<tr>
<td>120, Zdir</td>
<td>0.740 ± 0.008</td>
<td>1597</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>P(torr),Direction</th>
<th>$\mu Z$</th>
<th># Evs</th>
<th>S</th>
<th># evs for 90% conf.</th>
</tr>
</thead>
<tbody>
<tr>
<td>80, Xdir</td>
<td>0.370 ± 0.005</td>
<td>328</td>
<td>3.96</td>
<td>76</td>
</tr>
<tr>
<td>80, Zdir</td>
<td>0.398 ± 0.005</td>
<td>517</td>
<td>3.96</td>
<td>76</td>
</tr>
<tr>
<td>120, Xdir</td>
<td>0.154 ± 0.010</td>
<td>454</td>
<td>9.78</td>
<td>22</td>
</tr>
<tr>
<td>120, Zdir</td>
<td>0.268 ± 0.006</td>
<td>1597</td>
<td>9.78</td>
<td>22</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>P(torr),Direction</th>
<th>$\mu Z/\Delta X$</th>
<th># Evs</th>
<th>S</th>
<th># evs for 90% conf.</th>
</tr>
</thead>
<tbody>
<tr>
<td>80, Xdir</td>
<td>0.317 ± 0.007</td>
<td>328</td>
<td>5.11</td>
<td>42</td>
</tr>
<tr>
<td>80, Zdir</td>
<td>0.361 ± 0.005</td>
<td>517</td>
<td>5.11</td>
<td>42</td>
</tr>
<tr>
<td>120, Xdir</td>
<td>0.302 ± 0.007</td>
<td>454</td>
<td>4.84</td>
<td>97</td>
</tr>
<tr>
<td>120, Zdir</td>
<td>0.341 ± 0.004</td>
<td>1597</td>
<td>4.84</td>
<td>97</td>
</tr>
</tbody>
</table>

gives the number of events as

$$N = \frac{S^2 \cdot (\sigma_X^2 + \sigma_Z^2)}{(\mu_X - \mu_Z)^2}$$

(7.42)

To achieve a result that will give 90% confidence level for discriminating the directions, $S \geq 1.7$.

Using this definition for the significance and the number of events needed, the results for the X and Z directed runs in 80 and 120torr for the directionalities are summarized in Table 7.6.3.

The reason the number of events needed to get a 90% confidence level for the direction is low is due to the bin size to collect this information. The bins at the higher energies will increase the directional effect and will therefore decrease the number of events needed. It is interesting to see how the directionality in the Z direction, for 120torr is so much better than the directionality in Z for the X directed runs. Speculations about this have already been presented.
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Due to the oscillations in $\Delta X$ in the 120torr data, the two places in the table for the significance $S$ of this effect and the number of events needed to achieve 90% confidence are left blank.

It can be seen as well, that $\Delta X$ for the Z directed runs in 120torr is smaller than for the X directed runs. This confirms what has been seen already when the $\Delta X$ distributions were plotted separately in the smaller energy bins. As was discussed in Section 7.6.1, this might be due to the fact that the tracks are very short at these low energies in 120torr. This effect is of course taken care of when looking at the $\Delta Z/\Delta X$ distributions since the effect of $\Delta Z$ completely dominates this effect.

In general, this confirms that the angle variable $\Delta Z/\Delta X$ will be the best to analyze, since it removes any kind of irregular effects from the directionality.
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7.7 Head-Tail effect in the nuclear recoil data

It has been shown in the previous section that the prototype detector is indeed directional. It has also been shown how many events from a given direction are needed to know which direction the incoming particle came from. The next important step is to discuss if a head-tail effect can be seen with the, which way the charge is distributed along the track, how large the effect is and how many events are needed to establish the vector direction of the recoil.

The asymmetries used to describe the head-tail effect have been introduced in Chapter 4 already, but to remind the reader what these are, they were chosen to be

- **track → ZasymC**: Asymmetry in the Z direction as calculated using the Sum-line of the data record. The asymmetry is calculated as

$$track \rightarrow ZasymC = \frac{S_{\text{right}} - S_{\text{left}}}{S_{\text{right}} + S_{\text{right}}}.$$  

$S_{\text{left}}$ and $S_{\text{right}}$ are defined in Chapter 4.

- **track → asym**: Asymmetry in the X direction as calculated using the charge on the individual strips. The asymmetry is calculated as

$$track \rightarrow asym = \frac{Q_R - Q_L}{Q_R + Q_L}.$$  

Here $Q_L$ is defined as $\sum_{i=fhit}^{midstrip} q_i[i]$ and $Q_R$ is defined as $\sum_{i=midstrip}^{lhit} q_i[i]$. $fhit$ is the first strip with a pulse on it, $lhit$ is the last strip with a pulse and $midstrip = (lhit - fhit)/2$.

The Head-Tail effect is presented as a comparison between anti-parallel directed runs (for example between Zup and Zdown runs, or X1 and X16 runs). The reason to compare the asymmetries in this fashion is that there might be effects from the electronics that will distort the head-tail effect. If this is the case, looking at the differences between two anti-parallel runs will get rid of the effect. This is why runs from both directions were taken in each dimension (X and Z).

For these different definitions of the head-tail asymmetry, if it behaves as is
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expected, that means more charge at the tail of the track (beginning) than at the head of the track (the end of the track), the asymmetries should behave as follows:

- **Neutrons from X1 side:** In this case, for the X asymmetry \( \text{track} \rightarrow \text{asym} \) there should be more charge in \( Q_L \) since the lower numbered strips are hit first and less charge in \( Q_R \). This means asym should be less than zero.

- **Neutrons from X16 side:** In this case, \( \text{track} \rightarrow \text{asym} \) should be greater than zero, since there should be more charge in \( Q_R \) (higher numbered strips are hit first) and less charge in \( Q_R \).

- **Combining X1 and X16 signatures:** When comparing \( \text{track} \rightarrow \text{asym} \) from the X1 and X16 direction to one another \( \text{asym}_{X16} > \text{asym}_{X1} \)

- **Neutrons from Zup:** In this case, for the Z asymmetry \( \text{track} \rightarrow \text{ZasymC} \) there should be more charge in \( Q_L \) since the part of the track with the larger amount of charge is created closer to the readout board and is readout first. This means \( \text{ZasymC} \) should be less than zero.

- **Neutrons from Zdown:** In this case, \( \text{track} \rightarrow \text{ZasymC} \) should be greater than zero, since there should be more charge in \( Q_R \) (created farther from the readout) and less charge in \( Q_R \) (created closer to the readout).

- **Combining Zup and Zdown signatures:** When comparing \( \text{track} \rightarrow \text{ZasymC} \) from the Zup and Zdown direction to one another \( \text{asym}_{Zdown} > \text{asym}_{Zup} \)

First, the Head-Tail effect in the X directed runs is investigated and the results are presented for the 80torr and 120torr runs. Only data in the X16 direction was taken with the DD generator in 40torr, therefore no Head-Tail studies were performed on
this data. The Head-Tail analysis on the 80 and 120torr data in the X and the Z direction was performed only on the previously identified nuclear band of the data.

### 7.7.1 Sulfur recoil Head-Tail effect in the X direction

To measure the Head-Tail effect in the X direction, the asymmetry studied was introduced above as \( track \rightarrow asym \). This variable was studied for different energy bins. The energy bins were chosen differently for the 80torr and 120torr runs:

\[
NIP_{\text{bins}80\text{torr}} = [500, 1000, 2500, 5000, 7500]
\]  \hspace{1cm} (7.43)

\[
NIP_{\text{bins}120\text{torr}} = [500, 1000, 2500, 5000, 7500, 10000]
\]  \hspace{1cm} (7.44)

The reason the energy bins were chosen differently from the ones in the directionality section is due to the limited amount of data in the X directed runs, especially at 80torr. When computing the asymmetries in X, this number would be split up even more, into the X1 and X16 directions. This decreases the available statistics to the point, where fitting a Gaussian to the asymmetry distributions is not feasible. The available data in the energy bins defined in Equations (7.43) and (7.44) are plotted in Figure 7.25.

It can be seen in these plots, that there are not that many events available in total and choosing the energy bins coarser allows for a better fit of the asymmetries. The reason the lowest energy bin in the 80torr data is not removed is to show that it is not the choice of the larger energy bin that allows for the Head-tail discrimination at these low energy bins, but it is a real effect. This will be seen in the following.

The analysis of the Head-Tail effect is performed similar to the directional analysis. The asymmetry was histogrammed in every energy bin and a Gaussian fit to
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Figure 7.25: Available data for calculating the X asymmetry $\text{track} \rightarrow \text{asym}$ for the 80torr runs on the left and the 120torr runs on the right. The X1 directions are the red points and the X16 directions are the blue points.

The mean $\mu$ and standard deviation $\sigma$ of the Gaussian were then recorded. All the histograms of “$\text{track} \rightarrow \text{asym}$” showing the Gaussian fit, are shown in Appendix E), Figures F.1 and F.2. It can already be seen here that the last energy bin chosen has to few events and was therefore disregarded in both asymmetry plots.

The mean $\mu$ of the Gaussian distribution is then plotted for each energy bin, separately for the X1 and X16 direction. For the 80torr runs, this is shown in Figure 7.26.

It was expected that the charge in the beginning of a track is larger than in the end of the track. This would manifest itself in an asymmetry in the X16 direction that should be larger than in the X1 direction. As can be seen in Figure 7.26, this is exactly what is observed.

The number of events needed to achieve a $2\sigma$ separation in the head-tail effect for the 80torr, X directed runs can be calculated using again the equation

$$N_{80,X} = \frac{4 \cdot (\sigma_{X1}^2 + \sigma_{X16}^2)}{(\mu_{X1} - \mu_{X16})^2}$$

(7.46)
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Figure 7.26: X asymmetry \( \frac{Q_R - Q_L}{Q_R + Q_L} \) of the X directed neutron run in 80torr of CS\(_2\). The asymmetry in X is plotted for neutrons from the X16 side (blue) and neutrons from the X1 side (red). The reasons for the small number of energy bins is discussed earlier.

The resulting numbers in the different energy bins are shown in Figure 7.27.

The number of events needed to get the 2\(\sigma\) separation of the asymmetries is about 1000 events for track energies within the first energy bin and then drops down to higher energies.

For the 120torr run the asymmetry for the Head-tail, using the energy bins defined above, is plotted in Figure 7.28. The individual histograms for the different energy bins are shown in Appendix F), Figures F.3 and F.4. It can be seen in these histograms as well that the last energy bin should have not been used, since there
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Figure 7.27: Number of events needed to get a 2σ separation of the X asymmetry between X1 and X16 directed events in 80torr.

were too few events to justify a Gaussian fit to the distribution.

It can be seen that the asymmetries are nicely separated in the highest energy bin, but they are closer together at the lower energies. The lower statistics are hurting the results in this pressure as well. This result implies again that there is more charge at the beginning of a track than at the end.

The number of events needed to achieve a 2σ separation between the two anti-parallel, X directed runs in 120torr is shown in Figure 7.29.

The number of events needed is slightly lower than for the 80torr data, especially in the lowest energy bin. Why this is the case is not clear, since it would have been expected that asymmetry would be harder to resolve in higher pressures. This could
Figure 7.28: X asymmetry $\frac{Q_R - Q_L}{Q_R + Q_L}$ of the X directed neutron runs in 120torr of CS$_2$. Distributions for neutrons coming from the X16 side (blue) and the X1 side (red) are compared.

be the case for different reasons. First of all, the runs were not performed with absolutely identical setups. This could mean that the position of the neutron source might have been slightly different between runs. Also, the gas gain of the detector was adjusted to be about the same for the two runs. But a possibly higher gain in the 120torr run could have contributed to create this better result. It was also noticed that the noise was larger throughout the 80torr run. By investigating the head-tail in the Z directed runs, it might be possible to see the same effect.
Figure 7.29: Number of events needed to get a $2\sigma$ separation of the X asymmetry between X1 and X16 directed runs in 120torr.

### 7.7.2 Head-Tail effect in the Z direction

The asymmetry in the Z direction is calculated as $track \to Z_{asymC}$. The analysis procedure as introduced above is repeated for investigating the head-tail asymmetry in the Z direction. The asymmetry is histogrammed separately for different energy bins for the Zup and Zdown exposures. The various histograms can be found in Appendix F in Figures F.5 and F.6.

The histograms were all fit with a Gaussian distribution and the mean $\mu$ and spread $\sigma$ of this Gaussian were recorded. The same problem seen in the X directed runs arises here, which is the small number of statistics at higher energies for both runs. Therefore, the following plots will also all cut off at 6000NIPs. The available events for the 80 and 120torr runs are shown in Figure 7.30

The difference in the charge asymmetry in the Z directed data at 80torr is shown
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Figure 7.30: Available statistics for the 80torr, Z directed runs on the left and the 120torr Z directed runs on the right. The blue points correspond to events from the Zup side, the red points to events from the Zdown side.

in Figure 7.31.

Figure 7.31: Asymmetry $track \rightarrow Z_{asym C} = \frac{Q_R - Q_L}{Q_R + Q_L}$ of the Z directed neutron runs in 80torr of CS$_2$. The asymmetry in Z is plotted for neutrons from the Zup side (blue) and neutrons from the Zdown side (red).

It can be seen that the two distributions are nicely separated across all energy
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bins. This is a great result, since this allows for discrimination of the track direction even at 500NIPs, which corresponds to a 27keV Sulfur recoil.

What this means for the number of events needed to see a $2\sigma$ separation between the two is shown in Figure 7.32.

![Figure 7.32: Number of events needed for $2\sigma$ separation in track $\rightarrow$ ZasymC for the Z directed neutron runs in 80torr of CS$_2$.](image)

As was expected the number of events needed is below 10 events in all but one energy bin (the 1000 to 2000NIPs bin). To see this at such low energies is great. Especially since the pressure used is twice as high as was initially considered. Also, since the Z direction does not depend on the strip pitch used, this shows the potential to run a DRIFT like detector with less resolution than this prototype detector at a higher pressure.

This analysis was also performed on the Z directed data at 120torr. The two different distributions for Zup and Zdown events is shown in Figure 7.33.

This shows a similar result as the 80torr data. The separation of the two distri-
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\[
Z_{sym} = \frac{Q_R - Q_L}{Q_R + Q_L}
\]

Figure 7.33: Asymmetry \( Z_{sym} \) of the \( Z \) directed neutron runs in 120torr of CS\(_2\). The mean of the asymmetry in \( Z \) is plotted for neutrons from the \( Z_{up} \) side (blue) and neutrons from the \( Z_{down} \) side (red).

As expected, a much larger amount of events is needed to see \( 2\sigma \) separation in 120torr. Especially the lowest energy is affected by that. This result shows the expected result, that the charge asymmetry should be harder to resolve in the higher pressure runs.

For both runs, the asymmetry in \( Z \) for neutrons coming from the bottom of the detector, is smaller than the one for neutrons coming from the top. This means that the head-tail effect in the \( Z \) directed runs is found to be the expected one, with more charge at the beginning of a track than the end of a track.

For these runs, the head-tail asymmetries have been histogrammed for one large
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Figure 7.34: Number of events needed for $2\sigma$ separation in $\text{track} \rightarrow Z_{\text{sym}}C$ for the Z directed neutron runs in 120torr of CS$_2$.

energy bin from 500 to 5000NIPs, fitted with a Gaussian. The asymmetries are summarized in Table 7.5. It lists the mean $\mu$ of the Gaussian fit and the number of events that were recorded for each variable.

It can be seen in the table, that the asymmetries are consistent with the tracks creating more charges at the beginning (tail) of the track and less at the end (head). This is the expected result. It is also necessary to note that the asymmetries in

<table>
<thead>
<tr>
<th>asymmetry</th>
<th>$X_1\mu$</th>
<th>$X_1\text{ evs}$</th>
<th>$X_{16}\mu$</th>
<th>$X_{16}\text{ evs}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{asy}_80$</td>
<td>$0.110 \pm 0.042$</td>
<td>123</td>
<td>$0.167 \pm 0.042$</td>
<td>156</td>
</tr>
<tr>
<td>$\text{asy}_{120}$</td>
<td>$-0.039 \pm 0.044$</td>
<td>203</td>
<td>$0.064 \pm 0.047$</td>
<td>234</td>
</tr>
<tr>
<td>$Z_{\text{sym}}C_{80}$</td>
<td>$0.093 \pm 0.008$</td>
<td>229</td>
<td>$0.127 \pm 0.007$</td>
<td>192</td>
</tr>
<tr>
<td>$Z_{\text{sym}}C_{120}$</td>
<td>$0.050 \pm 0.005$</td>
<td>681</td>
<td>$0.091 \pm 0.006$</td>
<td>518</td>
</tr>
</tbody>
</table>

Table 7.5: Events needed for determining the direction of an incoming particle to a 90% confidence level
X and Z are not the same for both runs. This makes sense for the asymmetry in X. Since the charge will spread out over less strips, dividing the track in half can give different results when the tracks are significantly shorter. The asymmetries in Z should be more or less the same though, since the resolution in time is very good and a shorter track should give the same asymmetries in principle. What can explain the discrepancy, is the electronics. In 120torr, the drift velocity is 2/3 of the drift velocity in 80torr. This means the charge will take a longer amount of time to be read out by the electronics. Since the PreAmp used in this work has an automatic baseline reset, the longer charge collection time might cause it to distort the pulse with the baseline reset function. Since the head-tail asymmetry is still recorded in Z for 120torr runs, this will not be a concern for this measurement.

From the results in Table 7.5, the significances between the head-tail effects for Z directed and X directed runs can be calculated. This is done using:

\[ S = \frac{\mu_X - \mu_Z}{\sqrt{\frac{\sigma_X^2}{N_X} + \frac{\sigma_Z^2}{N_Z}}} \]  

(7.47)

This equation can also be used to calculate the number of events needed along each axis to achieve a 90% confidence level between asymmetries in the two directions for X and Z directed runs. This is done using Equation (7.47) with \( N_X = N_Z = N \):

\[ N = \frac{S^2 \cdot (\sigma_X^2 + \sigma_Z^2)}{(\mu_X - \mu_Z)^2} \]  

(7.48)

The resulting significances and needed numbers of events to reach a 90% confidence level are summarized in Table 7.6.

This summarizes what has already been said, that the head-tail asymmetry, even though present for the X directed runs is not as easily resolved and a larger amount of data is needed to assign a vector direction to a recoil in the X direction. It can also
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Table 7.6: Significances calculated for the asymmetries between X and Z directed runs

<table>
<thead>
<tr>
<th>Pressure</th>
<th>Comp Asyms</th>
<th>S</th>
<th># evs 90% conf</th>
</tr>
</thead>
<tbody>
<tr>
<td>80torr</td>
<td>asym X1 with X16</td>
<td>0.96</td>
<td>544</td>
</tr>
<tr>
<td>80torr</td>
<td>ZasymC Zup with Zdown</td>
<td>3.20</td>
<td>59</td>
</tr>
<tr>
<td>120torr</td>
<td>asym X1 with X16</td>
<td>1.56</td>
<td>247</td>
</tr>
<tr>
<td>120torr</td>
<td>ZasymC Zup with Zdown</td>
<td>5.25</td>
<td>55</td>
</tr>
</tbody>
</table>

be seen that the head-tail effect in the X direction is much worse for 80torr than it is for 120torr. As was mentioned before, this is most likely due to the noise observed during the run and possible gain variations during the two runs.

It is interesting to investigate what will happen when the two signatures, the directionality and the head-tail effect, are combined. This is presented in the following section.
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Table 7.7: Events needed for determining the vector direction of an incoming particle to a 90% confidence level combining the directionality and head-tail signatures

<table>
<thead>
<tr>
<th>Pressure</th>
<th># events</th>
<th>CL ( \Delta Z )</th>
<th>CL ( \Delta X ) track → asym</th>
<th>CL ( Z ) asymC</th>
<th>CCL</th>
</tr>
</thead>
<tbody>
<tr>
<td>80torr</td>
<td>32</td>
<td>86.2 %</td>
<td>31.9 %</td>
<td>90.6 %</td>
<td></td>
</tr>
<tr>
<td>120torr</td>
<td>50</td>
<td>77.8 %</td>
<td>55.5 %</td>
<td>90.1 %</td>
<td></td>
</tr>
<tr>
<td>80torr</td>
<td>18</td>
<td>73.4 %</td>
<td>65.4 %</td>
<td>90.8 %</td>
<td></td>
</tr>
<tr>
<td>120torr</td>
<td>25</td>
<td>61.2 %</td>
<td>74.5 %</td>
<td>90.1 %</td>
<td></td>
</tr>
</tbody>
</table>

7.8 Combining the results from directionality with the Head-Tail effect

Since the two signatures that are measured, the head-tail asymmetry in X and in Z and the directionality described as \( \Delta Z/\Delta X \), are independent of one another, the signatures can be combined. The reason to do this, is that combining the two signatures will result in less events needed to detect the vector direction of an incoming particle along each axis.

To calculate the combined confidence level for a certain number of events N, the significance of each signature is calculated using Equation (7.47). The confidence level (CL) of each signature is then calculated \((CL_{asym}, \ CL_{Z asymC} \) and \( CL_{\Delta Z/\Delta X} \)) and the combined confidence level (CCL) is found using

\[
CCL_X = 1 - (1 - CL_{asym}) \cdot (1 - CL_{\Delta Z/\Delta X})
\]

\[
CCL_Z = 1 - (1 - CL_{Z asymC}) \cdot (1 - CL_{\Delta Z/\Delta X})
\]

The results for this measurement are summarized in Table 7.8.

This shows, that considering both signatures in each direction does bring down the number of events needed to determine a three dimensional vector direction of a recoil track significantly. This significantly decreases the number of events needed
Chapter 7. Measurements of nuclear recoil tracks using neutron exposures

especially along the Z axis. It is also good to see that, when combining the signatures, the 80torr pressure will give better results, as is expected, since the tracks are longer and the ability to resolve tracks should be better. If the directionality of $\Delta Z$ is used instead of $\frac{\Delta Z}{\Delta X}$ for the 120torr runs (since this signature was better), the number of events would be significantly decreased as well.

It needs to be remembered though, that the number of events needed along each axis as presented in Table 7.8, is only true for events coming in perfectly aligned with one of the axes. If there are events that are not directed along either axis, significantly more events would be needed to make the same statement. The reason that it can not be accounted for these events is that it is not know what the values of the variables (asym, $Z_{asym}$, $\frac{\Delta Z}{\Delta X}$) are for events that come in from all directions. This could be done in simulation or may require extra measurements.
Chapter 8

Conclusions

It has been shown in this Dissertation that a high-resolution, GEM based, directional dark matter prototype detector has been successfully operated over an extended period of time. It has been shown that the prototype detector could be operated in gaseous $\text{CS}_2$ of 40, 80 and 120torr pressures over several weeks at a time without losing gain stability. The GEM has been proven to work well over these extended periods of time and can work as a reliable and relatively sturdy multiplication stage in a dark matter detector.

Furthermore it has been shown that the detector is indeed directional. Problems were presented that showed the limited capability of the prototype detector due to its size. For future studies of these low energy nuclear recoils induced by a $^{252}\text{Cf}$ source, it would be useful to implement a larger region of the detector. This way, selection effects due to the small size of the active detector region would be eliminated.

The analysis of the data concerning the head-tail asymmetry was successful in the Z direction and showed obvious problems in the X direction. It has been mentioned in the Chapter 7 that this could be due to the GEM. As mentioned then, the pitch of the GEM holes is about $150\mu m$. With the strip pitch being $200\mu m$, 

208
the two numbers are very close. Especially when only a region of 16 strips in X is implemented, any kind of accidental line up of the GEM holes with the strips could lead to a weakening of the head-tail effect in the X asymmetry. If a larger number of X strips had been implemented, the effect of the holes lining up with the strips would be eliminated statistically and probably yielding a much better result in the X direction. For a future detector setup, a different multiplication stage would probably be chosen. Possibly Micromegas [68] (Micromesh Gaseous structures) would work in combination with readout strips or possibly pixels. Another possibility would be to combine a charge readout with a scintillation readout. This could possibly decrease the number of events needed along each axis to below 10.

It is important to point out that the results on directionality and head-tail are from neutrons that are directed along the X and Z axes of the detector. To quote a result for WIMPs arriving along an arbitrary direction in the detector would require more measurements or detailed simulations. That is, our result of 11 events needed along each axis is a lower limit. This is true even if the WIMP wind arrives from the direction of “Cygnus” such that a detector in the Boulby Mine could be aligned so that the wind arrives in the X-Z plane. Ideally a detector should have full 3D tracking capabilities such that a WIMP wind arriving from an arbitrary direction can be seen.

Since it was mentioned before that the Z directed runs were really runs under an angle from the Z axis, this might already give an indication what the incident angle will do to the result. To really measure the impact of this, measurements in the laboratory would have to be performed in which the neutron source would be held fixed at some angle from the Z axis and data would be taken for example at every 10°. This would give a realistic idea of the events needed to detect an unambiguous WIMP signal from directional detection in a $CS_2$ based detector.

The measurements presented also show that there might be some room to change
Chapter 8. Conclusions

the pressure that DRIFT operates at. It can be seen that with a higher resolution in X, higher pressures are a viable option. Even using just the asymmetry in Z, higher pressures might be something that could be considered. Just increasing to 80torr would already increase the target mass of one DRIFT module by a factor of two.

Overall one can conclude that the described prototype detector can undergo various improvements to show that a higher resolution readout will be a useful tool in a directional dark matter detector.
Appendices

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Appendix A

Neutron Generator

The neutron generator used for the experiments mentioned before is a Deuterium-Deuterium neutron generator. The principle of this generator is described here.

The DD neutron generator exploits the reaction

\[
D + D \rightarrow n + ^4He
\]  

(A.1)

The neutrons being created in this reaction are monoenergetic at an energy of \(E_n = 2.5 MeV \pm 10\%\) and are emitted isotropically. The He nucleus is emitted in the exact opposite direction of the neutron.

The basic features of a sealed neutron tube are shown in Figure(A.1) [69].

Shown on the left side of the schematic is the ion source, which is comprised of the Gas Reservoir Element, the magnet, the rear and exit cathodes and the ion source anode. The setup shown here is also referred to as a Penning ion source. The gas reservoir element is used to heat or cool the gas inside the ion source and therefore control the gas pressure. A magnetic field is created by the magnet and a crossed electric field by putting the source anode at a positive potential, usually between 2
Appendix A. Neutron Generator

![Neutron Tube Schematic]

Figure A.1: Schematic that shows how the DD generator works to create neutrons.

and 7kV. In these crossed E and B fields, a plasma is formed which traps electrons. These electrons in turn will ionize the gas and create the ions needed in the D + D reaction. When operating the ion source under regular conditions, the ions produced are over 90% molecular ions. The ions are then extracted through the exit cathode.

The ions are then accelerated between the exit cathode and the accelerator electrode. They pass through the accelerator electrode and strike the target where they combine with other deuterium, creating the neutrons. The target is usually a thin film of metal (Titanium, scandium or zirconium) which will from metal hydrides when it is combined with hydrogen or its isotopes. The hydrides are made up of two deuterium atoms per metal atom and therefore the target will have a very high density of deuterium. The gas reservoir element uses the same metal hydrides as the
Appendix A. Neutron Generator

active material.

The neutrons created in the D-D reaction in the target will be isotropic but slightly peaked in the forward direction from the target. The energies of the neutrons will vary slightly (10%) depending on which direction from the target they are emitted.

The advantages of a neutron generator over a source like the $^{252}$Cf, are that the neutrons emitted are nearly monoenergetic and that the production of neutrons can be turned on and off on demand. This eliminates the need for constant shielding even when the source is not in use.
Appendix B

Expected interaction rates of $^{252}$Cf γ particles in the detector

The interaction rates for the γ particles created in the spontaneous fission process of the $^{252}$Cf source needs to be estimated as well. The reason to do so is to ensure that γ particles are not contaminating the neutron data. As mentioned in the previous section, the activity of the neutron source in March and April 2008 can be averaged to

$$A_{March/April2008} = 0.227\, mCi = 8.399 \cdot 10^6 \, \text{decays/s}. \quad (B.1)$$

It has also been mentioned before that there are approximately six γ’s for each neutron, such that the γ activity of the source is

$$A_\gamma = 6 \cdot 8.399 \cdot 10^6 \, \text{decays/s} = 5.039 \cdot 10^7 \, \gamma'/\text{s}\/.\quad (B.2)$$

The areas of the detector that the γ’s are emitted into are the same as in Equations 6.15 and 6.16 and the distances of the source from the active detector volume are
Appendix B. Expected interaction rates of $^{252}$Cf $\gamma$ particles in the detector

the same as discussed in the previous Section ($d_{X_{16}} \approx 34\,\text{cm}$, $d_{Z_{up}} \approx 15\,\text{cm}$ and $d_{Z_{down}} \approx 18\,\text{cm}$).

Using these numbers the, the number of $\gamma$ particles that are actually emitted into the active detector volume, are

$$A_{\gamma_{det,X_{16},Cf}} = 5.039 \cdot 10^7 \gamma's/s \cdot \frac{A_X}{4\pi d_{X_{16}}^2} = 3.469 \cdot 10^4 \text{s}^{-1}$$  \hspace{1cm} (B.3)

$$A_{\gamma_{det,Zu,Cf}} = 5.039 \cdot 10^7 \gamma's/s \cdot \frac{A_Z}{4\pi d_{Zu}^2} = 2.851 \cdot 10^4 \text{s}^{-1}$$  \hspace{1cm} (B.4)

$$A_{\gamma_{det,Zd,Cf}} = 5.039 \cdot 10^7 \gamma's/s \cdot \frac{A_Z}{4\pi d_{Zd}^2} = 1.980 \cdot 10^4 \text{s}^{-1}$$  \hspace{1cm} (B.5)

Using the durations of each neutron run given in Equations 7.1 to 7.4, the total number of $\gamma$’s emitted into the active detector volume during each neutron run are:

$$N_{\gamma_{det,80X,Cf}} = A_{\gamma_{det,X,Cf}} \cdot 107h = 1.3363 \cdot 10^{10} \gamma's$$  \hspace{1cm} (B.6)

$$N_{\gamma_{det,80Z,Cf}} = A_{\gamma_{det,Z,Cf}} \cdot 40h = 3.4783 \cdot 10^9 \gamma's$$  \hspace{1cm} (B.7)

$$N_{\gamma_{det,120X,Cf}} = A_{\gamma_{det,Z,Cf}} \cdot 89h = 1.1115 \cdot 10^{10} \gamma's$$  \hspace{1cm} (B.8)

$$N_{\gamma_{det,120Z,Cf}} = A_{\gamma_{det,Z,Cf}} \cdot 38h = 3.3304 \cdot 10^{10} \gamma's$$  \hspace{1cm} (B.9)

It needs to be remembered here that a lead brick of 5cm width was placed in front of the $^{252}$Cf source during the X directed runs. Lead attenuates $\gamma$ particles, it is not easily described in this case though, since the $\gamma$’s have a spectral energy distribution (see Figure 7.3). The attenuation of the $\gamma$’s in lead is energy dependent. A plot of the attenuation with respect to $\gamma$ energy is shown in Figure B.1.

Using this transmission probability for the X directed runs and the spectral energy distribution of the $\gamma$’s, the interaction probability of the $\gamma$ particles in 80 and 120torr CS$_2$ needs to be found. Again, this interaction probability is energy dependent. A plot of the interaction probability of $\gamma$’s from a $^{252}$Cf source is shown in Figure B.2.
Appendix B. Expected interaction rates of $^{252}\text{Cf}$ $\gamma$ particles in the detector

It can be seen in this Figure that lower energy $\gamma$ particles are more likely to interact in the gas. This effect counteracts the transmission probability of the lead which was larger for higher energy $\gamma$'s. Using these two plots, normalizing the $\gamma$ spectrum to the total number of $\gamma$'s being emitted into the active detector volume $N_\gamma$ for each direction and pressure of CS$_2$, the energy dependent number of $\gamma$'s expected to interact in the detector volume can be found. This is shown for $\gamma$'s in 80torr CS$_2$ for X directed particles in Figure B.3.

To find the total number of $\gamma$'s expected in the neutron data, the curve in Figure B.3 is integrated over all energies. With this, the expected amount of $\gamma$ contamination
Appendix B. Expected interaction rates of $^{252}$Cf $\gamma$ particles in the detector

\begin{figure}[h]
\centering
\includegraphics[width=\columnwidth]{interaction_rates.png}
\caption{Energy dependent interaction probability of a $\gamma$ particle in 80torr CS$_2$ in $\frac{1}{cm}$. This shows that lower energy $\gamma$’s are more likely to interact in the gas.}
\end{figure}

in the neutron runs is

\begin{align}
N_{exp\gamma_{80X}} &= 87 \tag{B.10} \\
N_{exp\gamma_{80Z}} &= 8516 \tag{B.11} \\
N_{exp\gamma_{120X}} &= 66 \tag{B.12} \\
N_{exp\gamma_{120Z}} &= 1395 \tag{B.13}
\end{align}

These numbers are found using the $\gamma$ efficiencies from the $^{60}$Co measurements. When these efficiencies are not included in the calculation, the expected number of $\gamma$ events
Appendix B. Expected interaction rates of $^{252}\text{Cf}$ $\gamma$ particles in the detector

![Graph](image)

Figure B.3: Energy dependent number of $\gamma$ particles interacting in 80torr CS$_2$. This is the actual number of $\gamma$’s expected to interact in the 107h long neutron run.

in the neutron data would be

\begin{align*}
N_{exp\gamma 80X, noeff} & = 13840 \quad \text{(B.14)} \\
N_{exp\gamma 80Z, noeff} & = 16014 \quad \text{(B.15)} \\
N_{exp\gamma 120X, noeff} & = 17264 \quad \text{(B.16)} \\
N_{exp\gamma 120Z, noeff} & = 22815 \quad \text{(B.17)}
\end{align*}
Appendix C

Removing $\gamma$ events from the data and Carbon and Sulfur discrimination

The two dimensional range versus NIPs plots from the Z directed run in 80torr CS$_2$ and the X and Z directed runs in 120torr are shown. These plots are used in the same way to remove $\gamma$ events from the neutron data as was presented in Section 7.4 for the X directed neutron data in 80torr.

The following figures show how the range versus NIPs plots of the neutrons compare to the expected ranges of Carbon and Sulfur recoils of a certain energy.
Appendix C. Removing $\gamma$ events from the data and Carbon and Sulfur discrimination

Figure C.1: Two dimensional range versus Energy in NIPs plot from 80torr, Z directed neutron run with the $^{252}$Cf source.

Figure C.2: Two dimensional range versus NIPs plot from the Z directed 80torr neutron run (blue) overlaid with the Z directed $^{60}$Co run (red) in 80torr CS$_2$. 
Appendix C. Removing $\gamma$ events from the data and Carbon and Sulfur discrimination

Figure C.3: Two dimensional range versus NIPs plot from the Z directed 80torr run showing the line that is used to remove the $\gamma$ events from the neutron data.

Figure C.4: Two dimensional range versus Energy in NIPs plot from 120torr, X directed neutron run with the $^{252}$Cf source.
Appendix C. Removing $\gamma$ events from the data and Carbon and Sulfur discrimination

Figure C.5: Two dimensional range versus NIPs plot from the X directed neutron run (blue) overlaid with the X directed $^{60}$Co run (red) in 120torr CS$_2$.

Figure C.6: Two dimensional range versus NIPs plot from the X directed 120torr run showing the line that is used to remove the $\gamma$ events from the neutron data.
Appendix C. Removing $\gamma$ events from the data and Carbon and Sulfur discrimination

Figure C.7: Two dimensional range versus Energy in NIPs plot from 120torr, Z directed neutron run with the $^{252}$Cf source.

Figure C.8: Two dimensional range versus NIPs plot from the Z directed neutron run (blue) overlaid with the Z directed $^{60}$Co run (red) in 120torr CS$_2$. 
Appendix C. Removing $\gamma$ events from the data and Carbon and Sulfur discrimination

Figure C.9: Two dimensional range versus NIPs plot from the Z directed 120torr run showing the line that is used to remove the $\gamma$ events from the neutron data.

Figure C.10: Two dimensional range versus Energy in NIPs plot from Z directed run in 80torr CS$_2$ compared with the expected R2 versus NIPs plot for Carbon and Sulfur recoils.
Appendix C. Removing $\gamma$ events from the data and Carbon and Sulfur discrimination

Figure C.11: Two dimensional range versus Energy in NIPs plot from X directed run in 120torr CS$_2$ compared with the expected R2 versus NIPs plot for Carbon and Sulfur recoils.

Figure C.12: Two dimensional range versus Energy in NIPs plot from Z directed run in 120torr CS$_2$ compared with the expected R2 versus NIPs plot for Carbon and Sulfur recoils.
Appendix D

Extra figures and tables

Various additional tables and pictures are summarized in this Appendix. They are mentioned in the text of the dissertation when appropriate.

Table D.1: Available runs with the $^{60}$Co source in June 2008. The drift field for all runs is set at $E_D = (700 \pm 35) V/cm$.

<table>
<thead>
<tr>
<th>File name</th>
<th>P(torr)</th>
<th>$\Delta V_G(V)$</th>
<th># events</th>
<th>direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>100406192008_60Co_(0-2)_2D_v1.dat</td>
<td>80</td>
<td>430</td>
<td>1122</td>
<td>X1</td>
</tr>
<tr>
<td>170106202008_60Co_(0-8)_2D_v1.dat</td>
<td>80</td>
<td>430</td>
<td>4183</td>
<td>Zdown</td>
</tr>
<tr>
<td>134706242008_60Co_0_2D_v1.dat</td>
<td>120</td>
<td>464</td>
<td>318</td>
<td>X1</td>
</tr>
<tr>
<td>102306252008_60Co_up_0_2D_v1.dat</td>
<td>120</td>
<td>464</td>
<td>161</td>
<td>Zdown</td>
</tr>
<tr>
<td>131306262008_60Co-zdir_0_2D_v1.dat</td>
<td>120</td>
<td>464</td>
<td>15</td>
<td>Zdown</td>
</tr>
<tr>
<td>114006182008_background_0_2D_v1.dat</td>
<td>80</td>
<td>464</td>
<td>53</td>
<td></td>
</tr>
</tbody>
</table>
Appendix D. Extra figures and tables

Table D.2: Available background runs with all sources removed. These runs were performed in between neutron exposures. The drift fields $E_D$ were always set at $E_D = (700 \pm 35)V/cm$.

<table>
<thead>
<tr>
<th>File name</th>
<th>P(torr)</th>
<th>$\Delta V_G$(V)</th>
<th># events</th>
<th>$\Delta t$ (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>124003122008_background_0_2D_v1.dat</td>
<td>80</td>
<td>430</td>
<td>26</td>
<td>0.8</td>
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<tr>
<td>132803122008_background_0_2D_v1.dat</td>
<td>80</td>
<td>430</td>
<td>65</td>
<td>5.3</td>
</tr>
<tr>
<td>112704142008_background_0_2D_v1.dat</td>
<td>120</td>
<td>464</td>
<td>116</td>
<td>10.15</td>
</tr>
<tr>
<td>053504192008_background_0_2D_v1.dat</td>
<td>120</td>
<td>464</td>
<td>296</td>
<td>15.85</td>
</tr>
</tbody>
</table>

Table D.3: Noise values $\mu_{\text{noise}(i)}$ and $\sigma_{\text{noise}(i)}$ of each channel for the 2D readout electronics and gain factor used to adjust the strip-to-strip gain variations.

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\mu_{\text{noise}(i)}$</th>
<th>$\sigma_{\text{noise}(i)}$</th>
<th>threshold</th>
<th>gain adjust</th>
</tr>
</thead>
<tbody>
<tr>
<td>1X</td>
<td>0.211</td>
<td>0.152</td>
<td>0.667</td>
<td>0.914</td>
</tr>
<tr>
<td>2X</td>
<td>0.128</td>
<td>0.064</td>
<td>0.320</td>
<td>1.159</td>
</tr>
<tr>
<td>3X</td>
<td>0.026</td>
<td>0.084</td>
<td>0.278</td>
<td>0.915</td>
</tr>
<tr>
<td>4X</td>
<td>0.049</td>
<td>0.035</td>
<td>0.154</td>
<td>1.114</td>
</tr>
<tr>
<td>5X</td>
<td>0.000</td>
<td>0.123</td>
<td>0.369</td>
<td>0.907</td>
</tr>
<tr>
<td>6X</td>
<td>0.000</td>
<td>0.072</td>
<td>0.216</td>
<td>1.071</td>
</tr>
<tr>
<td>7X</td>
<td>0.000</td>
<td>0.103</td>
<td>0.309</td>
<td>0.886</td>
</tr>
<tr>
<td>8X</td>
<td>0.040</td>
<td>0.135</td>
<td>0.445</td>
<td>1.096</td>
</tr>
<tr>
<td>9X</td>
<td>0.000</td>
<td>0.080</td>
<td>0.240</td>
<td>0.855</td>
</tr>
<tr>
<td>10X</td>
<td>0.062</td>
<td>0.080</td>
<td>0.302</td>
<td>1.133</td>
</tr>
<tr>
<td>11X</td>
<td>0.000</td>
<td>0.064</td>
<td>0.192</td>
<td>0.963</td>
</tr>
<tr>
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<td>0.000</td>
<td>0.080</td>
<td>0.240</td>
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<tr>
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<td>0.080</td>
<td>0.240</td>
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<tr>
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<td>0.053</td>
<td>0.159</td>
<td>1.026</td>
</tr>
<tr>
<td>15X</td>
<td>0.019</td>
<td>0.080</td>
<td>0.259</td>
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<td>16X</td>
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<td>0.102</td>
<td>1.113</td>
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<tr>
<td>1Y,2Y</td>
<td>0.065</td>
<td>0.036</td>
<td>0.173</td>
<td>0.933</td>
</tr>
<tr>
<td>3Y,4Y</td>
<td>0.000</td>
<td>0.037</td>
<td>0.111</td>
<td>0.947</td>
</tr>
<tr>
<td>5Y,6Y</td>
<td>0.033</td>
<td>0.017</td>
<td>0.084</td>
<td>1.014</td>
</tr>
<tr>
<td>7Y,8Y</td>
<td>0.008</td>
<td>0.179</td>
<td>0.545</td>
<td>0.974</td>
</tr>
<tr>
<td>9Y,10Y</td>
<td>1.541</td>
<td>2.485</td>
<td>8.996</td>
<td>0.965</td>
</tr>
<tr>
<td>11Y,12Y</td>
<td>0.795</td>
<td>0.106</td>
<td>1.113</td>
<td>1.009</td>
</tr>
<tr>
<td>13Y,14Y</td>
<td>0.583</td>
<td>0.460</td>
<td>1.963</td>
<td>1.055</td>
</tr>
<tr>
<td>15Y,16Y</td>
<td>0.008</td>
<td>0.073</td>
<td>0.227</td>
<td>1.034</td>
</tr>
</tbody>
</table>
Appendix D. Extra figures and tables

Table D.4: Available $^{55}$Fe calibration runs for all data taking runs. The drift fields were always set at $E_D = (700 \pm 35) \text{ V/cm}$

<table>
<thead>
<tr>
<th>File name</th>
<th>P(torr)</th>
<th>$\Delta V_G$(V)</th>
<th>$\mu$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>091011012007,55Fe_0-2D_v1.dat</td>
<td>40</td>
<td>400</td>
<td>$2.982 \cdot 10^4$</td>
<td>$1.297 \cdot 10^4$</td>
</tr>
<tr>
<td>095111012007,55Fe_0-2D_v1.dat</td>
<td>40</td>
<td>398</td>
<td>$3.621 \cdot 10^4$</td>
<td>$1.179 \cdot 10^4$</td>
</tr>
<tr>
<td>120911012007,55Fe_y-0-2D_v1.dat</td>
<td>40</td>
<td>398</td>
<td>$0.726 \cdot 10^4$</td>
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<tr>
<td>094811022007,55Fe_x,0-2D_v1.dat</td>
<td>40</td>
<td>398</td>
<td>$2.997 \cdot 10^4$</td>
<td>$1.183 \cdot 10^4$</td>
</tr>
<tr>
<td>144311052007,55Fe_y-0-2D_v1.dat</td>
<td>40</td>
<td>407</td>
<td>$1.901 \cdot 10^4$</td>
<td>$0.273 \cdot 10^4$</td>
</tr>
<tr>
<td>152511052007,55Fe_y-0-2D_v1.dat</td>
<td>40</td>
<td>407</td>
<td>$1.905 \cdot 10^4$</td>
<td>$0.632 \cdot 10^4$</td>
</tr>
<tr>
<td>160511062007,55Fe_x,(0-1),2D_v1.dat</td>
<td>40</td>
<td>411</td>
<td>$2.867 \cdot 10^5$</td>
<td>$0.751 \cdot 10^5$</td>
</tr>
<tr>
<td>081211072007,55Fe_x,0-2D_v1.dat</td>
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<td>416</td>
<td>$3.438 \cdot 10^5$</td>
<td>$2.653 \cdot 10^5$</td>
</tr>
<tr>
<td>102511072007,55Fe_y-0-2D_v1.dat</td>
<td>40</td>
<td>416</td>
<td>$0.964 \cdot 10^5$</td>
<td>$0.189 \cdot 10^5$</td>
</tr>
<tr>
<td>130503102008,55Fe_0-2D_v1.dat</td>
<td>80</td>
<td>430</td>
<td>$3.426 \cdot 10^4$</td>
<td>$0.892 \cdot 10^4$</td>
</tr>
<tr>
<td>130503102008,55Fe_0-2D_v1.dat</td>
<td>80</td>
<td>430</td>
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<td>$1.024 \cdot 10^4$</td>
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<td>091003172008,55Fe,(0-1),2D_v1.dat</td>
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<td>095903172008,55Fe,(1-3),2D_v1.dat</td>
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<td>214104142008,55Fe,(0-2),2D_v1.dat</td>
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<tr>
<td>045604232008,55Fe,(0-2),2D_v1.dat</td>
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<td>464</td>
<td>$1.966 \cdot 10^4$</td>
<td>$0.493 \cdot 10^4$</td>
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Table D.5: Available neutron exposure data for all runs, all runs are performed with a drift field of $E_D = (700 \pm 35)V/cm$.

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<th>File name</th>
<th>P(torr)</th>
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<th># events</th>
<th>direction</th>
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<td>3141</td>
<td>from X1</td>
</tr>
</tbody>
</table>
Appendix D. Extra figures and tables

Figure D.1: Schematic of the 8 channel PreAmp chip used and explanations of all the inputs

- i8: inputs
- o8: outputs
- SA: calibration enable
- SE: calibration enable select
- S2 - S4: calibration select (S4 is LSB)
- J: calibration input
- JG: calibration ground (0V, terminates J to 50Ω)
- T1, T2: peaking time setting: 0 0 0.6μs (default), 3 0 1.2μs, 0 3 2.4μs, 3 3 4.0μs
- G1, G2: gain settings: 0 0 200mV/FC (default), 3 0 100mV/FC, 0 3 50mV/FC, 3 3 33mV/FC
- B: baseline reference check
- BA: baseline adjust (to be changed with DG) -300mV → 0V
- G: ground (0V)
- +1: positive supply common bias circuit and channels 1 – 4 (+3V)
- +2: positive supply common channels 5 - 8
- DG: drivers ground (0V or to be changed together with DG)
- D+1: drivers positive supply channels 1 – 4 (+3V)
- D+2: drivers positive supply channels 5 – 8 (+3V)
- PG1: input FETs ground channels 1 – 4 (0V)
- PG2: input FETs ground channels 5 – 8 (0V)
- nc: not connected (GND if if possible)
Appendix D. Extra figures and tables

Figure D.2: The PC boards holding the inverting electronics for the 1D detector are shown on the left. The connector on the left side of the box connects the inverting electronics to the feedthrough that then connects to the output channels inside the vessel.
Figure D.3: Diagram of the structure of the LabView software

1st: Initialize WFD

- User stops WFDs manually
- Program writes a set of numbers to the buffer of each WFD channel and then reads them back
- If the read numbers are the same as the written numbers, memory test passed
- If the read numbers are not the same as the written numbers, memory test failed
- User restarts the WFDs manually

2nd: Readout WFD

- Check that length of the buffer to be read out is not greater than actual buffer size if max pulse height is less then threshold continue with next step
- If max pulse height is greater then threshold, restart WFD and begin again
- If coincidence is turned off, this step is skipped
- Read out all N channels including the coincidence channel
- After readout every channel is looked at individually
- If coincidence is turned on, maximum pulse height of the data record is found
- Maximum pulse height is greater then threshold then:
  - If max pulse height is greater then threshold, area under the pulse found from the maximum pulse height is calculated from first to last zero crossing in time
  - The entire signal for each strip (entire buffer that was read out) and a sum of all the signals, is plotted on the front panel
  - A sum of charge for the event is calculated by summing areas of all individual pulses
  - WFD is restarted now
  - The entire buffer that was read out, and a sum of all the signals, is plotted on the histogram and all the signals on all channels are stored in a file of the form: "filename": "today's date".txt. A "type". Integer: number from 0 to 5; it is 0 if number of event is between 0 and 100, etc.
  - After this the program starts again from the first until a preset number of events is collected

Appendix D. Extra figures and tables
Figure D.4: Schematic of the old Trigger scheme used until January 2008
Figure D.5: Schematic of the new Trigger used from January 2008 on
Appendix D. Extra figures and tables

Figure D.6: Picture of the inside of the new Summing unit. The boards holding the electronic circuit can be seen with all their necessary connections.
Figure D.7: Circuit diagram of the custom summer unit designed and built at UNM to improve the Trigger
Appendix D. Extra figures and tables

Figure D.8: Schematic of the entire electronics setup used with the 1D board readout electronics.

Figure D.9: Schematic of the FEE setup used inside the vessel for the 2D detector.
Figure D.10: Schematic of the box used to program the PreAmps and supply voltage to the electronic components inside the vessel
Figure D.11: Poisson output for which the wire potential is set at the optimal value.
Appendix D. Extra figures and tables

Figure D.12: Poisson output for which the wire potential is chosen high with respect to the optimal configuration.
Figure D.13: Poisson output for which the wire potential is chosen low with respect to the optimal configuration.
Appendix E

Distributions of $\Delta X$, $\Delta Z$ and $\Delta Z/\Delta X$

In the following, all the various distributions of $\Delta X$, $\Delta Z$ and $\Delta Z/\Delta X$ are shown for 80 and 120torr and X and Z directed runs. Refer to the captions of the Figures to reference the pressure and direction of the histogram.
Figure E.1: Histograms of $\Delta X$ from the Z directed run in 120torr. The histograms go from the 500 to 1000 NIPs bin in the upper left hand corner to the 9000 to 10,000NIPs bin in the lowest histogram in 1000NIPs bin steps.
Appendix E. Distributions of $\Delta X$, $\Delta Z$ and $\Delta Z/\Delta X$

Figure E.2: Histograms of $\Delta X$ from the X directed run in 120torr. The histograms go from the 500 to 1000 NIPs bin in the upper left hand corner to the 9,000 to 10,000NIPs bin in the lowest histogram, in 1000NIPs bin steps.
Appendix E. Distributions of $\Delta X$, $\Delta Z$ and $\Delta Z/\Delta X$

Figure E.3: Histograms of $\Delta Z$ from the Z directed run in 120torr. The histograms go from the 500 to 1000 NIPS bin in the upper left hand corner to the 9000 to 10,000NIPS bin in the lowest histogram in 1000NIPS bin steps.
Appendix E. Distributions of $\Delta X$, $\Delta Z$ and $\Delta Z/\Delta X$

Figure E.4: Histograms of $\Delta Z$ from the X directed run in 120torr. The histograms go from the 500 to 1000 NIPs bin in the upper left hand corner to the 9,000 to 10,000NIPs bin in the lowest histogram, in 1000NIPs bin steps.
Appendix E. Distributions of $\Delta X$, $\Delta Z$ and $\Delta Z/\Delta X$

Figure E.5: Histograms of $\Delta Z/\Delta X$ from the Z directed run in 120torr. The histograms go from the 500 to 1000 NIPs bin in the upper left hand corner to the 9000 to 10,000NIPs bin in the lowest histogram in 1000NIPs bin steps.
Appendix E. Distributions of $\Delta X$, $\Delta Z$ and $\Delta Z/\Delta X$

<table>
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<th>0</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<td>RMS</td>
<td></td>
<td></td>
<td></td>
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- **$dX/dZ 10$**
  - Entries: 161
  - Mean: 0.2515
  - RMS: 0.1905

- **$dX/dZ 11$**
  - Entries: 186
  - Mean: 0.3448
  - RMS: 0.2295

- **$dX/dZ 12$**
  - Entries: 138
  - Mean: 0.4308
  - RMS: 0.3527

- **$dX/dZ 13$**
  - Entries: 70
  - Mean: 0.4857
  - RMS: 0.5061

- **$dX/dZ 14$**
  - Entries: 57
  - Mean: 0.5855
  - RMS: 0.6427

- **$dX/dZ 15$**
  - Entries: 49
  - Mean: 0.4692
  - RMS: 0.448

- **$dX/dZ 16$**
  - Entries: 46
  - Mean: 0.6489
  - RMS: 0.5156

- **$dX/dZ 17$**
  - Entries: 25
  - Mean: 0.7594
  - RMS: 0.6178

- **$dX/dZ 18$**
  - Entries: 26
  - Mean: 0.7486
  - RMS: 0.5136

- **$dX/dZ 19$**
  - Entries: 17
  - Mean: 0.7175
  - RMS: 0.5939

---

Figure E.6: Histograms of $\Delta Z/\Delta X$ from the X directed run in 120torr. The histograms go from the 500 to 1000 NIPs bin in the upper left hand corner to the 9,000 to 10,000NIPs bin in the lowest histogram, in 1000NIPs bin steps.
Appendix E. Distributions of $\Delta X$, $\Delta Z$ and $\Delta Z/\Delta X$

Figure E.7: Histograms of $\Delta X$ from the Z directed run in 80torr. The histograms go from the 500 to 1000 NIPs bin in the upper left hand corner to the 9,000 to 10,000NIPs bin in the lowest histogram, in 1000NIPs bin steps.
Appendix E. Distributions of $\Delta X$, $\Delta Z$ and $\Delta Z/\Delta X$

![Histograms](image)

Figure E.8: Histograms of $\Delta X$ from the X directed run in 80torr. The histograms go from the 500 to 1000 NIPs bin in the upper left hand corner to the 9000 to 10,000NIPs bin in the lowest histogram in 1000NIPs bin steps.
Appendix E. Distributions of $\Delta X$, $\Delta Z$ and $\Delta Z/\Delta X$

<table>
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<tr>
<th>$dZ$ (mm)</th>
<th>Entries</th>
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<th>RMS</th>
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<td>1.436</td>
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Figure E.9: Histograms of $\Delta Z$ from the $Z$ directed run in 80torr. The histograms go from the 500 to 1000 NIPs bin in the upper left hand corner to the 9,000 to 10,000NIPs bin in the lowest histogram, in 1000NIPs bin steps.
Appendix E. Distributions of $\Delta X$, $\Delta Z$ and $\Delta Z/\Delta X$

Figure E.10: Histograms of $\Delta Z$ from the $X$ directed run in 80torr. The histograms go from the 500 to 1000 NIPs bin in the upper left hand corner to the 9000 to 10,000NIPs bin in the lowest histogram in 1000NIPs bin steps.
Appendix E. Distributions of $\Delta X$, $\Delta Z$ and $\Delta Z/\Delta X$

Figure E.11: Histograms of $\Delta Z/\Delta X$ from the Z directed run in 80torr. The histograms go from the 500 to 1000 NIPs bin in the upper left hand corner to the 9,000 to 10,000NIPs bin in the lowest histogram, in 1000NIPs bin steps.
Figure E.12: Histograms of $\Delta Z/\Delta X$ from the X directed run in 80torr. The histograms go from the 500 to 1000 NIPs bin in the upper left hand corner to the 9000 to 10,000NIPs bin in the lowest histogram in 1000NIPs bin steps.
Appendix F

Distributions of Head-Tail asymmetries

In the following, various distributions of the Head-Tail asymmetries are shown for 80 and 120 torr and X and Z directed runs. Refer to the captions of the Figures to reference the pressure and specific asymmetry histogramed.
Appendix F. Distributions of Head-Tail asymmetries

Figure F.1: Histograms of $track \rightarrow asym$ from the X1 directed runs in 80torr. The energy bins for the histograms are: Top left corner: 500 to 1000; Top right corner: 1000 to 2500NIPs; Middle left: 2500 to 5000NIPs; Middle right: 5000 to 7500NIPs; bottom: 7500 to 10000NIPs.
Appendix F. Distributions of Head-Tail asymmetries

Figure F.2: Histograms of \( \text{track} \rightarrow \text{asym} \) from the X16 directed runs in 80torr. The energy bins for the histograms are: Top left corner: 500 to 1000; Top right corner: 1000 to 2500NIPs; Middle left: 2500 to 5000NIPs; Middle right: 5000 to 7500NIPs; bottom: 7500 to 10000NIPs.
Appendix F. Distributions of Head-Tail asymmetries

Figure F.3: Histograms of $track \rightarrow asym$ from the X1 directed runs in 120torr. The energy bins for the histograms are: Top left corner: 500 to 1000; Top right corner: 1000 to 2500NIPs; Middle left : 2500 to 5000NIPs; Middle right: 5000 to 7500NIPs; bottom left: 7500NIPs to 10000NIPs; bottom right: 10000NIPs to 12500NIPs
Appendix F. Distributions of Head-Tail asymmetries

Figure F.4: Histograms of \( \text{track} \rightarrow \text{asym} \) from the X16 directed runs in 120torr. The energy bins for the histograms are: Top left corner: 500 to 1000; Top right corner: 1000 to 2500NIPs; Middle left: 2500 to 5000NIPs; Middle right: 5000 to 7500NIPs; bottom left: 7500NIPs to 10000NIPs; bottom right: 10000NIPs to 12500NIPs
Appendix F. Distributions of Head-Tail asymmetries

Figure F.5: Histograms of \( \text{track} \to \text{ZasymC} \) from the Zup directed runs in 80torr. The energy bins for the histograms are: Top left corner: 500 to 1000; then from the left to the right in each row is a 1000NIPs bin increase very time; bottom: 9000 to 10000NIPs.
Appendix F. Distributions of Head-Tail asymmetries

Figure F.6: Histograms of \textit{track} \rightarrow ZasymC from the Zdown directed runs in 80torr. The energy bins for the histograms are: Top left corner: 500 to 1000; then from the left to the right in each row is a 1000NIPs bin increase very time; bottom: 9000 to 10000NIPs.
Appendix F. Distributions of Head-Tail asymmetries

Figure F.7: Histograms of track $\rightarrow ZasympC$ from the Zup directed runs in 120torr. The energy bins for the histograms are: Top left corner: 500 to 1000; then from the left to the right in each row is a 1000NIPs bin increase very time; bottom: 9000 to 10000NIPs.
Appendix F. Distributions of Head-Tail asymmetries

Figure F.8: Histograms of track $\rightarrow ZasymC$ from the Zdown directed runs in 120torr. The energy bins for the histograms are: Top left corner: 500 to 1000; then from the left to the right in each row is a 1000NIPs bin increase very time; bottom: 9000 to 10000NIPs.
References


References


References


References


[42] SRIM simulations performed by P. Majewski, University of Sheffield.


References


[64] Daniel Snowden-Ifft private communication.


References
