THE DRIFT DIRECTIONAL DARK MATTER DETECTOR
AND FIRST STUDIES OF THE HEAD-TAIL EFFECT

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Measurement of the direction of the elastic nuclear recoil track and ionization charge distribution along it, gives unique possibility for unambiguous detection of the dark matter WIMP particle. Within current radiation detection technologies only Time Projection Chambers filled with low pressure gas are capable of such measurement. Due to the character of the electronic and nuclear stopping powers of low energy nuclear recoils in the gas, an asymmetric ionization charge distribution along their tracks may be expected. Preliminary study of this effect, called Head-Tail, has been carried out here using the SRIM simulation program for Carbon and Sulfur in 40 Torr carbon disulfide, as relevant to the DRIFT detector. Investigations were focused on ion tracks projected onto the axis of the initial direction of motion in the energy range between 10 and 400 keV. Results indicate the likely existence of an asymmetry influenced by two competing effects: the nature of the stopping power and range straggling. The former tends to result in the Tail being greater than the Head and the latter the reverse. It has been found that for projected tracks the mean position of the ionization charge flows from 'head' to 'tail' with the magnitude depending on the ion type and its energy.

Keywords: Dark Matter; Nuclear Recoils; Head-Tail; DRIFT; SRIM; WIMP

1. Introduction

It has been demonstrated by the Dark Matter searching experiment DRIFT\(^1\) using Time Projection Chambers (TPC) filled with low pressure CS\(_2\) that the direction of few mm long nuclear recoil tracks can be measured. However, due to the limited spatial resolution of the readout and ionization charge diffusion in the large detector volume, its distribution along the low energy nuclear recoil track is difficult to reconstruct.

In this work preliminary results of simulations of the energy loss and ionization charge distribution along tracks of Carbon and Sulfur ions in 40 Torr CS\(_2\) (\(\rho=1.67\cdot10^{-4}\) g/cm\(^3\)) are presented. The so-called Head-Tail
effect, describing the location of the majority of the ionisation charge either at the beginning (Tail) or at the end (Head) of the track as a function of ion energy and diffusion has been studied. SRIM$^2$ and TRIM programs were used to calculate stopping powers for ions in gases, to investigate with Monte Carlo generators the energy loss and ionization charge distribution along the ion track on an event-by-event basis.

2. SRIM

The Stopping and Range of Ions in Matter (SRIM) simulation program calculates as a function of energy: the electronic ($S_e$) and nuclear ($S_n$) energy loss, range and longitudinal and lateral straggling of ions moving in matter. They have been calculated here for ion energies up to 500 keV. To understand the behaviour along the tracks they are plotted in Fig. 1 and Fig. 2 against ion range, the ion energies marked here on the plot at 50 keV intervals.

As can be seen at higher energies the electronic energy loss is dominant and decreases with energy where at lower values the nuclear energy loss becomes greater than the electronic. For example for Sulfur ions the nuclear energy loss starts to dominate already at an energy of 100 keV. This means that energy loss along the ion track is not continuously decreasing. This has an impact on the density of the ionization charge along the track and makes the head-tail effect energy dependent.

In the nuclear interactions secondary nuclear recoils are created. Although 3-4 times higher energy is needed to create an electron-ion pair by
nuclear recoils than by electrons, they are a source of ionization.

![Fig. 2. Lateral (solid line) and longitudinal (dashed line) straggling/range as a function of range for Carbon (■) and Sulfur (▲) ions with energy is marked up to 500 keV with an interval of 50 keV.]

Due to continuous collisions with gas atoms the direction of the moving ions become deviated from the original path. This causes fluctuations in the ion’s range, described by the lateral and longitudinal straggling and depending on ion energy (see Fig 2). One can see that ions slowing down experience increasing straggling relative to the drift length they have ahead, which rises sharply at the very end of the track.

Tables calculated by SRIM are used in the Monte Carlo generator program called TRIM. In addition to on-line histogramming of various quantities, TRIM results are also recorded event by event in two different formats. The first is included in the file called COLLISON.TXT generated either in quick simulation, where for every ion collision its current energy, position in 3D and type of secondary recoils with their initial energy is recorded, or in full nuclear recoil cascade simulation, where information about the energies and positions of all created nuclear recoils is added. TRIM creates also an output file called EXXYZ which, though with superior spatial resolution to the other outputs, delivers information only about ion energy loss along the track. The latter format has been chosen here for the Head-Tail effect analysis.

3. TRIM Simulation and Results Analysis

For each ion with a given energy $10^4$ events were recorded and further analysed. The energies used were for Sulfur: from 10 to 100 with a step of 10 keV then up to 250 with a step of 25 keV and up to 400 with a step
of 50 keV and Carbon from 10 to 100 with a step of 10 keV then up to 200 keV with a step of 25 keV and up to 300 with a step of 50 keV. Each event in the TRIM output EXYZ file contained on average 100 collision points with information about: current ion energy, the 3D coordinate of the collision point and energy loss, for which the sum equals the initial energy of the ion. For Carbon and Sulfur ions the number of ionization charges was calculated using W-values taken from. For each ion, a W-value was used at every collision according to its current energy. Note that the actual value of W at energy below 20 keV is not well known and values used here are based on an extrapolation of the function obtained from the polynomial fit to the existing data.

Based on this approximation the Head-Tail effect has been studied for three different configurations of ion interaction points: along the track, projected onto the line between the beginning and the end of the track and projected onto the axis of the initial ion direction. Because of the range straggling of ions with the same energy, the position of each interaction projected point has been normalised to the projected range of the ion.

![Figure 3](image-url)

Fig. 3. Sulfur and Carbon ion range in CS$_2$ as a function of the energy, calculated with SRIM (▲ and ▼) and taken from (○ and □).

### 3.1. Ion Ranges

Using coordinates of the first and the last point of the ion track its projected range has been calculated. Fig. 3 shows results for Sulfur and Carbon ions in CS$_2$ in comparison with data from. There is very good agreement for Sulfur but a large discrepancy for Carbon ions for which results from this paper are more than twice smaller than in.

In the conversion of the energy loss into ionization charge, the number
of electrons attached with no loss to CS$_2$ molecules, creating CS$_2^-$ and called Negative Ions Pairs (NIPs), was summed for each Carbon and Sulfur ion energy. Fig. 4 shows, as a function of NIPs, the range of nuclear recoils together with the range of alpha particles and electrons calculated with TRIM and ESTAR$^4$, respectively.

![Fig. 4. Sulfur (⊙), Carbon (❏), alpha (▼) and electron (▲) range in CS$_2$ as a function of ionization charge (NIPs) created. NIPs for Sulfur and Carbon were calculated using the W-values from $^3$ while for alpha particles and electrons a constant value of W=19 eV was used. To calculate the range of electrons the ESTAR program was used for energies from 10 to 125 keV with steps 2.5, 5 and 10 up to 20, 60 and 100 keV, respectively. Results for the alpha particle ranges are for energies from 10 to 150 with a step of 10 keV.](image)

Table 1. Ranges of 103 keV $^{206}$Pb recoils in pure and binary gases at STP measured and simulated with TRIM. Values from measurement are taken from.$^5$ 1σ of the simulated range distributions is 10% of the tabulated mean values for all gases except Xe for which 1σ is 15%. Measurement uncertainty is ±2µm.

| Gas    | Ar | Xe | CH$_4$ | C$_2$H$_4$ | Air | N$_2$ |
|--------|----|----|--------|-----------|-----|------|
| Measurement [µm] | 79 | 44 | 84 | 58 | 83 | 80 |
| SRIM [µm] | 73 | 36 | 95 | 61 | 80 | 74 |

The NIP values were calculated using W-value=19 eV. As one can see the range of electrons with the same number of NIPs as nuclear recoils is one order of magnitude greater than the range of recoils. This demonstrates that a TPC operating with 40 Torr CS$_2$ has great separation power between electron and nuclear recoils. However, it shows also that the range of nuclear recoils and alpha particles are close to each other, with a difference not greater than 1-2 mm for tracks a few mm long, often also elongated due to the charge thermal diffusion.

To check the consistency of the SRIM results with existing measure-
ments, the range of 103 keV $^{206}$Pb recoils in several pure and binary gases at STP was calculated and compared with results from. The results are shown in Table 1 indicating in most cases less than a 10% difference. Similar differences between measurements and simulation were observed for 5-6 MeV alpha particles from Rn and Po decays in 40 Torr CS$_2$.

3.2. Head-Tail

Along with the event-by-event information on ion energy loss, TRIM also delivers histograms accumulated on-line and showing distributions of average values of several quantities as a function of target depth. With default initial TRIM settings the target depth corresponds to projection onto the axis of the initial direction of ion motion. One of the histograms shows distributions of the average ionization energy loss by ion and secondary recoils. An example of such a distribution, for 1000 Sulfur ions with energy of 100 keV, is shown in Fig. 5. One can see ionization energy loss by ion, secondary recoils and by the sum of them. The latter is compared with scaled results from the EXYZ TRIM output file analysis. Both show the same character of the ionization energy loss along the target depth indicating here that more energy is lost at the beginning of the track (Tail) than at the end (Head). However, this distribution is along the target depth regardless of the ion range which, due to straggling, varies from ion to ion. This is likely not the case in an actual experiment where recoils are detected on an event-by-event basis and charge distribution along the track is measured.
with respect to its projected range. Thus for this work we study the energy loss and Head-Tail effect also using the EXYZ output file.

For Sulfur and Carbon ions the distributions of ionization charge were studied along: the track, projection onto a line between the first and last point of the track, and projection onto the axis of the initial ion motion. The latter were studied with and without diffusion. Diffused NIPs were redistributed in space according to the thermal diffusion formula:

$$\sigma = \sqrt{\frac{2k_B T}{e}} \sqrt{\frac{L}{E}}$$

where: $k_B$ is Boltzmann constant, $T$ ambient temperature, $e$ electron charge, $E$ drift electric field and $L$ drift distance. After numerical simplifications a diffusion formula was used of form: $\sigma[mm] = 0.72 \sqrt{\frac{L[m]}{E[kV/cm]}}$ for three different drift lengths $L$: 0.1, 0.3 and 0.5 m and electric field in the DRIFT IIb detector $E= 0.58$ kV/cm.

Fig. 6. Ionization charge distribution along Sulfur track (normalised to its range): (a) along the drift path, (b) projected onto the line between the beginning and end of the track, (c) projected onto the direction of the initial motion, (d) randomly diffused with maximum drift path of 50 cm and projected onto the direction of the initial motion. Displayed distributions are for the following ion energies: from 10 to 100 with a step of 10 keV then up to 250 with a step of 25 keV and up to 400 with a step of 50 keV.

Figs. [6] and [7] show NIP distributions along the Sulfur and Carbon tracks, respectively. For both, as expected, the ionization charge distributions along the line following the ion’s motion (a) are not featured with a sharp rise at the end caused by the straggling. The negative slope of the distributions is very clear down to 40 keV and 20 keV for S and C, respec-
tively from which at lower energies (where nuclear energy loss dominates) they become flat.

![Graphs showing track length versus NIPs for different energies and ion types.](image)

Fig. 7. The same as in Fig 6 for Carbon tracks

Intermediate distributions of the charge projected onto a line between the track start and end point were studied. As one can see in (b) these still have negative slope but the sharp rise at the end is now clearly visible. The shape of distributions with projection onto the axis of the initial direction of motion is shown in (c). For Sulfur this is almost flat with a very sharp rise at the end, while for Carbon it remains with negative slope. An example of the impact of the diffusion caused by 0.5 m long drift, the maximum likely in DRIFT II, can be seen in Figs. 6d and 7d.

For diffused distributions the Head-Tail effect was studied by calculation of the mean position of the distribution as a function of ion energy and drift length. Fig. 8 shows the position of the mean along Carbon and Sulfur ion tracks with the head-tail effect dependent mainly on the ion energy. Points above 50% are for ion tracks with greater ‘head’ than ‘tail’ and those below for ions with the reversed effect.
Fig. 8. Position of the mean of the charge distribution along Carbon (solid line) and Sulfur (dashed line) ion tracks showing the Head-Tail effect as a function of energy and for different maximum drift distances: 10 (○), 30 (▼) and 50 (▲) cm. Points above 50 % indicate that more ionization charge is created at the end (Head) while those below that level, at the beginning (Tail) of the track.

4. Conclusions

In this work preliminary results of the Head-Tail effect of Carbon and Sulfur ions in low pressure CS$_2$ gas used in DRIFT detectors have been presented. Results were obtained using SRIM and TRIM simulation packages together with W-values available from existing data above ion energies of 20 keV. For lower ion energies W-values have been extrapolated using a polynomial fit to the existing data ranging from 20 to 300 keV. Results indicate the existence of the Head-Tail effect resulting respectively for Carbon and Sulfur greater Head for energies below 70 and 350 keV, above which Tail starts to dominate. As shown Head-Tail effect depends on the W-value which below 20 keV may be greater than values used in this work. This could impact significantly on the number of ionisation charge at the Head of the track and could cause the Tail to become dominant at lower energy.

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