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Simulations of the nuclear recoil head–tail signature in gases relevant to directional dark matter searches

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ABSTRACT

We present the first detailed simulations of the so-called head–tail effect of nuclear recoils in gas, the presence of which is vital to directional WIMP dark matter searches. We include comparison simulations of the range and straggling of carbon, sulphur and fluorine recoils in low pressure gas. However, the prime focus is a detailed investigation of carbon and sulphur recoils in 40 Torr negative ion carbon disulfide, a gas proposed for use in large scale directional detectors. The focus is to determine whether the location of the majority of the ionization charge released and observed from a recoil track in carbon disulfide is at the beginning (tail) of the track, at the end (head) or evenly distributed. We used the SRIM simulation program, together with a purpose-written Monte Carlo generator to model production of ionizing pairs, diffusion and basic readout geometries relevant to potential real detector scenarios, such as under development for the DRIFT experiment. The results indicate the likely existence of a head–tail track asymmetry but with a magnitude critically influenced by several competing factors, notably the *W*-value assumed, the drift distance and diffusion, and the recoil energy.

1. Introduction

Measurement of the direction of a low energy (≈1 keV/amu) nuclear recoil track and the ionization charge distribution along it, resulting from the elastic scattering of a target nucleus by an incoming WIMP (Weakly Interacting Massive Particle), provides a route towards the unambiguous identification of WIMPs as being responsible for the galactic dark matter [1]. Amongst current radiation detection technologies only Time Projection Chambers filled with low pressure gas, appear capable of such a measurement. This concept has been utilized by the directional dark matter search experiments DRIFT [2], NEWAGE [3], MIMAC [4] and DM-TPC [5] using Time Projection Chambers (TPCs) filled with low pressure CS_2 and CF_4. In these detectors attempts are currently made to reconstruct the orientation of the low energy nuclear recoil tracks, typically of a few millimetres in length. However, due to the character of the electronic and nuclear stopping powers of low energy nuclear recoils in gas, an asymmetric ionization charge distribution along their tracks may also be expected. Thus additional information on the absolute direction of recoils might be available. Such potential information on the track sense is termed the head–tail effect, for instance describing the location of the majority of the ionization charge as being either at the beginning half (tail) or at the end half (head) of the track. It is known that if this information can clearly be extracted in a detector this would, by breaking the forward-back degeneracy in the direction of recoils from WIMPs, have a dramatic impact on the potential directional sensitivity to dark matter. In particular, it could mean that of order ×10 fewer detected WIMPs would be needed to identify a directional signal [6].

Realisation of this gain would greatly increase the feasibility of building a large dedicated low pressure TPC detector capable of a definitive identification of dark matter. It is thus vital to understand whether, and to what magnitude, the head–tail effect is likely to be present, in both principle and practice. Recently some experimental evidence for head–tail asymmetry has been observed for F recoils in 100–380 Torr CF_4 [5]. Observation of the effect there was possible due to the use of relatively high energy recoils (>200 keV) and of a short drift gap to minimize diffusion. However, a realistic directional detector for dark matter will require sensitivity to much lower energies and with much larger volumes, where diffusion will likely be a significant issue. It is recognized that use of negative ion CS_2 gas can provide a route to large detectors here since in this case the charge carrier in the gas is CS_2 ions rather than electrons. The result is much lower diffusion during transit

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to the readout, so that drift distances can be longer and hence detector volumes much larger (order m^3) [2].

Measurement of the effect in a more realistic scenario for dark matter searches such as this is more difficult to perform. This is due to the limited spatial resolution imposed by the current readout technologies used with larger detectors, namely the Multiwire Proportional Counters (MWPCs) as in DRIFT, but also due to the greater ionization charge diffusion tolerated in order to maximize the size of the detectors. Some preliminary experimental measurements have nevertheless been possible so far with DRIFT itself [7]. These results do indicate a small head–tail effect even at S-recoil energies below 40 keV. However, in view of the importance of the issue for directional dark matter detection and the need to understand better the physical processes, so as to help optimise implementation of possible head–tail discrimination in a large detector with improved readout resolution, it is useful to undertake detailed simulations of the head–tail response and start to make theoretical predictions. This is the objective of the work presented here. In this light it should be noted that although comparison with the limited available head–tail data from DRIFT is of interest (see Section 3) the purpose here is not to detail a complete head–tail simulation for a specific detector such as DRIFT II but to explore the issue in a more generic fashion.

So far some basic theoretical predictions of the head–tail effect in binary gases have been performed by Hitachi, i.e. [8]. These results were based on Linear Energy Transfer calculations and ion projected range estimations from the SRIM (Stopping and Range of Ions in Matter) software package [9]. The obtained Bragg-like curves indicated that more ionisation charge is produced at the tail than at the head of the track, regardless of the ion type or energy. However, that work did not attempt to account for straggling, or address the issue of diffusion and the influence of track reconstruction geometry. In this work we present first detailed results of simulations of the energy loss and ionization charge distribution along tracks of carbon and sulfur ions in 40 Torr CS_2 ($\rho = 1.67 \times 10^{-4}$ gcm^{-3}), together with, for completeness, some comparison results for the ionization energy loss and straggling for fluorine ions in CF_4 ($\rho = 4.73 \times 10^{-4}$ gcm^{-3}). The head–tail effect is studied as a function of ion energy and diffusion in C and S but also in relation to the effect of straggling.

2. Simulation procedures and SRIM results

The basis of this work is firstly the SRIM software package and its incorporated TRIM (Transport of Ions in Matter) track generator Monte Carlo program. SRIM is a code commonly, and primarily, used for predictions of parameters relevant to ion implantation, sputtering and transportation in solid materials. However, it is also successfully used to simulate interactions in gases. Example comparison between ion range measurements in gases and results from SRIM calculations are shown in Table 1. SRIM was used here to produce tables as a function of energy of both the electronic (S_e) and nuclear (S_n) energy loss, range, longitudinal and lateral straggling of nuclear recoils (ions) in the gaseous target chosen. In this context straggling is defined, as used within TRIM, as the second moment of the distribution. The TRIM component is then used to generate many individual simulated tracks. This allows initial investigation of the energy loss distribution along individual raw recoil ion tracks and their secondaries, on an event-by-event basis. To complete the process, to give relevance to real detector scenarios, it is then necessary to convert, using the known average energy to create electron–ion pairs (W-value), the energy loss along each recoil track into ionization charges, or number of Negative Ion Pairs (NIPs), distributed along the track. Finally, it is necessary to account for the effects of diffusion of the tracks through a realistic drift volume (taken here to be up to 50 cm) and of the effects of projection onto readout axes. An in-house Monte Carlo was written for these latter stages, with appropriate values for the W to NIPs conversion factor, changing as a function of ion energy.

Table 1
Ranges of 103 keV ^{206}Pb recoils in pure and binary gases at STP measured and calculated with SRIM. Values from measurement are taken from [16]. 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 ±2 μm.

Gas	Measurement [μm]	SRIM [μm]
Ar	79	73
Xe	44	36
CH_4	84	95
C_2H_4	58	61
Air	83	80
N	80	74

In this work we calculate parameters for the selected recoil ions using energies up to 500 keV. Figs. 1 and 2 show SRIM results for the energy loss, lateral and longitudinal straggling, plotted against recoil ion range for ion energies selected at 50 keV intervals. As can be seen in these figures, at higher energies the electronic energy loss is dominant and decreases with decreasing energy, whereas at lower values the nuclear energy loss becomes greater than the electronic and increases with decreasing energy, at least initially. For example, for sulphur ions the nuclear energy loss starts to dominate at 100 keV. This means that the energy loss along the ion track is not continuously decreasing, as might naively be expected.

Due to continuous collisions with gas atoms the direction of moving ions also deviates from their original path. This causes fluctuations in the recoil ions range described by the lateral and longitudinal straggling as a function of ion energy. This parameter, divided by the range, is shown in Fig. 2. Here one can see that as the ions slow down they experience increasing straggling relative to the drift length they have ahead, rising sharply at the very end of the track.

The amount of energy loss due to nuclear interactions as a function of ion energy is presented in Fig. 3. The difference in nuclear energy loss between the different ions is clearly seen here. For carbon ions 50% or more of the total energy is lost via nuclear interactions for energies E < 20 keV, whereas in fluorine and sulphur the

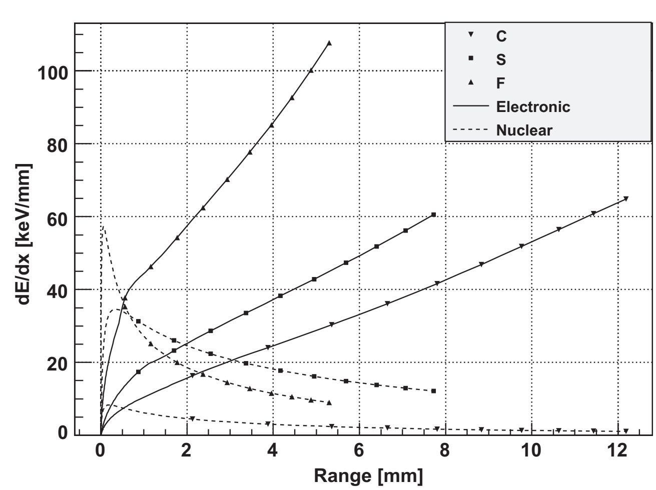

Fig. 1. Ionization energy loss dE/dx as a function of ion range in the medium, calculated with SRIM. Energy losses in electronic (solid line) and nuclear (dashed line) channels are shown for Sulfur (■) and Carbon (▼) ions in 40 Torr CS_2 and Fluorine (▲) in 100 Torr CF_4. Ion energy is marked up to 500 keV with an interval of 50 keV.