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Track Reconstruction Progress from the DMTPC directional dark matter experiment

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Abstract

The Dark Matter Time Projection Chamber (DMTPC) collaboration is developing prototype detectors to measure both the energies and directions of nuclear recoils. The intended application is to exploit the expected directional anisotropy of dark matter velocities at Earth to unambiguously observe dark matter induced recoils. The detector consist of low-pressure CF_4 TPC's with CCD cameras, PMT's, and charge amplifiers for readout. This talk gives an overview of the experiment and describes recent advances in hardware and analysis.

Selection and peer review is the responsibility of the Conference lead organizers, Frank Avignone, University of South Carolina, and Wick Haxton, University of California, Berkeley, and Lawrence Berkeley Laboratory

Keywords:

1. Introduction

The motion of the solar system around the center of the galaxy is expected to give rise to a preferred direction of incidence for WIMPs fixed in galactic coordinates [1]. When measured in lab coordinates, the preferred direction shifts with the rotation of the earth in a predictable way, creating a powerful discriminant against terrestrial backgrounds, such as neutrons. In order to take advantage of this information, a detector capable of measuring the direction of low energy nuclear recoils is necessary. In particular, due to the direction asymmetry being measured, it is most important to be able to measure the sense of the recoils; angular resolution and even measurement of the full 3D angle are somewhat less important [2].

Low-energy recoils lose energy very quickly in media, so, to measure the direction, it is either necessary to have exceedingly fine resolution or to use a diffuse target to extend the length of the track. The Dark Matter Time Projection Chamber (DMTPC) collaboration uses the latter approach, employing diffuse ($\approx$ 50 Torr) CF_4 gas as a target. The use of CF_4 provides sensitivity mostly to the spin-dependent WIMP coupling, due to the constituents' relatively low mass and the high nuclear spin factor of ^{19}F [3].

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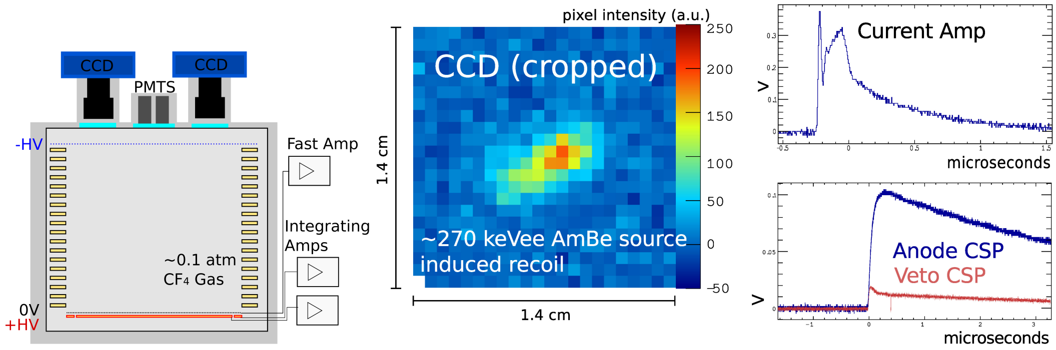


Figure 1. (Left) A schematic of a DMTPC detector. (Right) An example neutron-induced nuclear recoil in a prototype DMTPC detector.

The DMTPC detector prototypes aim to demonstrate sufficient directional reconstruction ability to measure the expected anisotropy of dark matter-induced recoils; setting competitive limits with non-directional experiments is not currently a priority.

2. The DMTPC Detector

The DMTPC detector, described in detail in [4][5][6], consists of low-pressure gas TPC's with a micromesh amplification region. The cathode and anode are both made up of fine meshes, with high optical transparency. The electrons from primary ionization are drifted to the amplification region, where they avalanche with a gas gain of approximately 50,000. The CCD cameras, which are focused on the amplification region, image the scintillation from de-exciting ions in the amplification gap, providing the primary means of readout. To improve the signal-to-noise ratio, the camera pixels are generally binned in hardware. Additionally, amplifiers on the electrodes measure both the total induced charge as well as the current between the ground mesh and anode. The current amplifier is sensitive to the rise time of the electron peak, which is helpful in estimating the Δz of the track [7]. PMT's measure the light production over time, also offering some sensitivity to Δz.

Figure 1 shows a schematic of the detector design along with an example nuclear recoil from a prototype detector [6].

3. Track Reconstruction Improvements

Figure 2 depicts an example nuclear recoil track in the CCD along with the parameters that may be reconstructed. Of crucial importance for a directional detector is the axial angle ϕ as well as the sense of the track along the axis. Sensitivity to the sense of recoils comes from stopping power of a low-energy recoil being monotonically decreasing, so that more energy is deposited at the front of the track than at the ends.

To find track candidates, a custom cluster-finding algorithm is used (a hysteresis threshold algorithm with a sliding lower threshold for adding additional camera bins to the track). The algorithm also estimates which bins contain energy deposition from the track.

An estimate of the energy is available from the measured intensity in the CCD pixels identified as a part of the track, while the centroid provides an estimate of the location of the recoil. The range is estimated by the longest distance between bins above a secondary, tuned, threshold. The principal axis from a principal component analysis is used for an estimate of the axial angler, and the resolution can be estimated by computing the second moment about that axis. The sense can be estimated in a simple way by dividing each track in half along its axis and computing which half has more energy. However, this method requires picking the bounds of the track correctly, which is a difficult problem given the read noise in the CCD. For very short tracks (only a few bins), the result of the algorithm is sensitive to the addition or subtraction of a single bins on either side of the track, and the performance degrades.

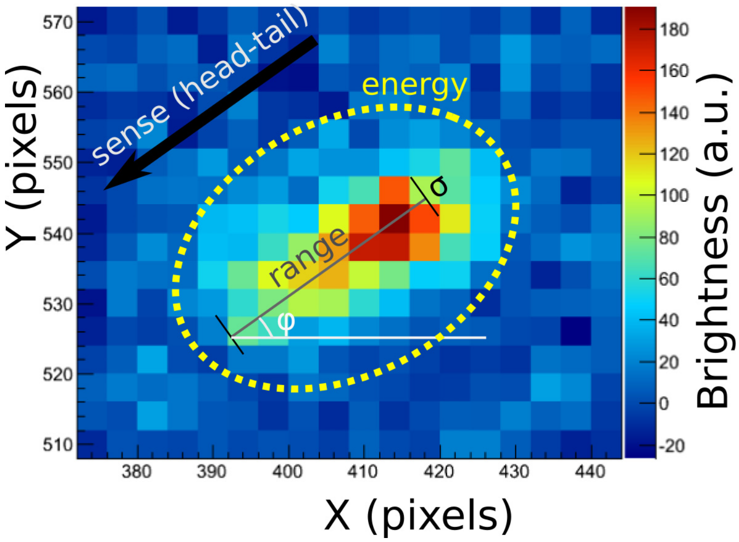


Figure 2. The parameters reconstructed from the CCD image of a recoil.

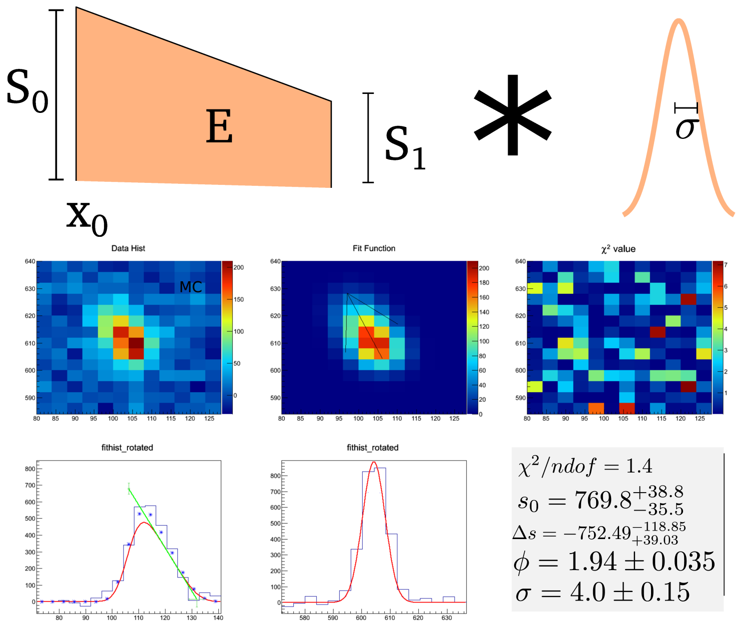
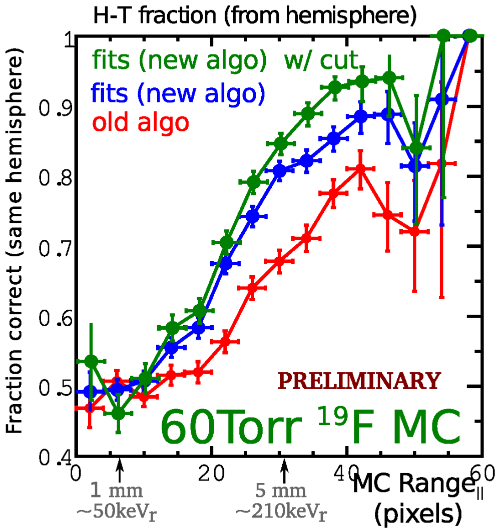


Figure 3. (Above) Sketch of the energy-loss model used in fitting. (Below) An example two-dimensional fit to a 60 Torr Monte Carlo recoil.



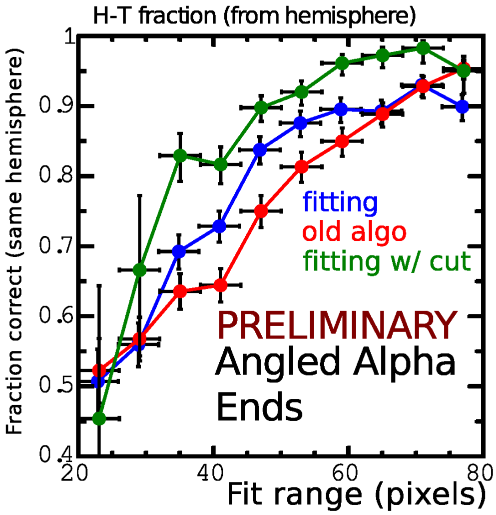


Figure 4. These plots depict the head-tail, or sense, performance vs. range in camera units using different algorithms. On the left are simulated nuclear recoils in 60 Torr CF_4 while on the right are α particles truncated such that only the last part of the track enters the drift volume.

To improve performance, a model-based fit has been developed. The camera bins near nuclear-recoil-like tracks are fit in two dimensions to a simplified energy loss model. The fit parameters are the start position, the axial angle, the energy, the resolution, and two stopping power parameters (see Figure 3). All parameters have estimates available and physically motivated bounds, which can be used to restrict the phase space of the seven-parameter fit. The sense can then be determined by the difference in the stopping power parameters.

The use of a fit provides the ability to make various cuts on tracks without the right form (poor χ^2) and to estimate the likelihood of having chosen the correct sense (by comparing the difference in stopping power parameters to its uncertainty or doing a likelihood ratio test between the two senses). Work is ongoing on optimizing these cuts, but an example performance using Monte Carlo is shown in Figure 4(a), showing significant improvement over the previous algorithm.

While a neutron source may be used to probe the performance of the algorithm, the uncertainty in the expected angular distribution of the recoils makes evaluation difficult in practice. An alternative is to use an α source angled and located such that only a small fraction of the energy (50-200 keV) of the α particle enters the amplification region near the cathode. The α has lower stopping power than a ^{19}F or ^{12}C recoil of similar energy, and the placement at the cathode maximizes the track diffusion. However, improved performance in sense reconstruction of the α should also translate into improved performance for nuclear recoils. The result for angled α's from ^{241}Am is shown in Figure 4(b).

Even with the improvements, the ability to reconstruct sense is poor at low energies. This is because low-energy recoils are very short, and the diffusion from the drift process limits the resolution of the detector very quickly (except very close to the anode). From simulation, we find that the sense performance is strongly dependent on the ratio of the track's projected length to the diffusion scale. It is possible to increase the length of recoils by lowering the pressure, albeit at the cost of less target mass. The collaboration is currently redesigning amplification regions to allow for stable operation at lower pressures without sparking.

4. Amplification Region Development

DMTPC amplification region development has focused on the realization of a triple mesh amplification region. Three fine, mostly transparent, meshes can be arranged to create two back-to-back amplification regions with a shared

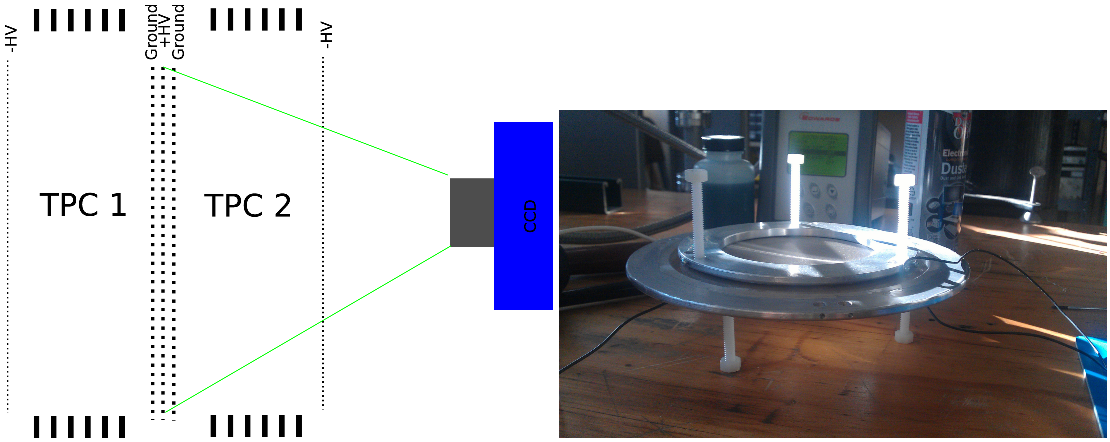


Figure 5. Left: Schematic of a triple mesh. Right: example small-scale prototype.

anode mesh. This design allows the imaging of two TPC's with a single camera, thus doubling the achievable fiducial volume without increasing the camera cost.

Prototypes (See Figure 5) on the scale of 10 cm have been built and operated in a small test stand. Achievable gas gains before sparking, as measured with a ^{55}Fe, are similar to a mesh-plate amplification region with the same gap size (e.g. ~60,000 at 60 Torr with a 0.5 mm amplification gap).

By modifying the applied potentials from (Ground)-(+HV)-(Ground) to a (Ground)-(+HV)-(++HV) configuration, it is possible to transform the same design into a double-stage amplification region (although for only one of the TPC's). Using this configuration, gas gains in excess of 500,000 have been measured with ^{55}Fe at 30 Torr. For α's, however, gas gains above about 120,000 lead to sparking (presumably due to the Raether limit[8], which limits the total number of electrons in an avalanche before a spark develops). The same would be true of nuclear recoils above some energy, as the ionization density will be even higher (For example, the electronic stopping power of a 200 keV recoil is comparable to the stopping power at the α Bragg peak [9]). The sparking introduces a limit to the usable gain for particles with a given stopping power at a given pressure. At the same time, lowering pressure permits increased gain, suggesting similar signal to noise may be achieved at any pressure.

5. Outlook

The current goal of the collaboration is to build a m^3-scale detector capable of directional detection of low-energy nuclear recoils. At an operating pressure of 30 torr, such a detector would have a total mass of about 150 grams. Replication may be used to further increase target mass. The detector will employ the triple-mesh technique so that four TPC's may be imaged by two sets of cameras. Construction is expected to be completed by the end of summer 2014.

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