Directional dark matter detection with the DMTPC m³ experiment

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Abstract. Directional reconstruction provides a unique way to positively identify signal interactions induced by dark matter particles, owing to the motion of the Earth through the galactic dark matter halo. Directional information can additionally serve as a powerful discriminant against neutron (and neutrino-induced) backgrounds that have the same final-state signature as a signal interaction. The Dark Matter Time Projection Chamber (DMTPC) collaboration uses gas-based TPC technology, with both optical and charge readout, to measure the directional anisotropy of nuclear recoils induced by particles traversing the detector volume. Here, we present preliminary results from recent calibration runs of the DMTPC m³ detector in a surface laboratory, as well as a study of its projected directional sensitivity.

Dark matter makes up approximately 85% of the matter in the universe [1]. Its gravitational influence at the galactic and intergalactic scale has been elucidated by a broad range of astrophysical and cosmological measurements. Yet the particle constituents of dark matter remain a complete mystery, with several major unknowns, including their mass, interaction cross section and spatial distribution in our galaxy. The particle nature of dark matter is one of the fundamental questions about the universe today.

1. Directional detection

Directional, like direct, detection attempts to detect dark matter directly from astrophysical sources by exploiting the elastic scattering of dark matter particles off of target nuclei. The aim of directional detection, however, is to measure the direction (as well as the kinetic energy) of nuclear recoils and thereby reconstruct the angular spectrum of incoming dark matter particles such as WIMPs. Directional detection thus provides a natural way to correlate an observed excess of signal events with an astrophysical phenomenon in the celestial sky, an important requisite for a conclusive identification of dark matter. An excess of events correlated with the galactic motion would provide unambiguous proof of a WIMP source.

The directional signature of dark matter arises from the Earth’s motion with respect to the galactic rest frame. As seen by an observer on Earth, a ‘wind’ of dark matter appears to come from the direction of the Cygnus constellation. The direction of this wind is expected to change by approximately 90° every twelve hours, creating large anisotropies in recoil direction [2]. In contrast, the backgrounds in most experiments are roughly isotropic in the detector coordinate system, lacking this sidereal variation. Directionality therefore provides powerful discrimination against backgrounds and has unique ability to positively identify dark matter by testing the astrophysical-origin hypothesis of a candidate signal.
2. DMTPC

The Dark Matter Matter Time Projection Chamber (DMTPC) experiment employs time projection chamber (TPC) technology, with low-pressure CF$_4$ gas as both detection volume and target. Equipped with CCD-camera, PMT and charge readout systems, DMTPC detectors are capable of measuring the direction of incoming dark matter particles by reconstructing the energy, time and vector direction of nuclear recoils with respect to the Earth’s motion.

A schematic of the DMTPC detection principle is shown in Figure 1. A vacuum chamber is evacuated, then filled with low-pressure (30–75 Torr) CF$_4$ gas. The gas sits inside a uniform electric field created by the potential difference between cathode (-HV) and ground mesh planes and shaped by step-down field cage rings at the outer extremity of the fiducial volume. Incoming (dark matter) particles scatter elastically off of a $^{19}$F or $^{12}$C nucleus\(^1\), freeing ionization electrons that drift inside the electric field towards the ground plane. The electrons eventually reach an amplification region, consisting of closely-spaced ground and anode (+HV) mesh planes, 0.6–1 mm apart, with a high electric field in between. There, they undergo proportional multiplication, creating scintillation light that is detected by CCD cameras and PMTs positioned opposite the amplification region. The integrated charge signal is read out via pre-amplifiers.

![Figure 1. A schematic of the DMTPC detection principle.](image)

A CCD camera sees a two-dimensional projection of the ionization electrons onto the amplification plane. From a camera image associated to an event, a Principle Component Analysis (PCA) is used to determine the axis of the track, which can then be transformed to an axial angle in galactic coordinates. The range and transverse width of a track are also measured, in addition to the energy of the track, equal to the sum of CCD counts over all illuminated pixels belonging to the track. The non-uniformity of the \(dE/dx\) profile is used to extract the ‘head-tail’, or vector, sense of the track.

The charge readout system is used for an additional energy measurement, background discrimination (by requiring coincidence with the CCD readout) and possibly trigger. The PMT readout is used for additional timing information and eventually \(z\) fiducialization. With these methods, the DMTPC collaboration has shown directional sensitivity to nuclear recoils in a series of larger-and-larger prototypes \([3,4]\).

\(^1\) Due to the small target mass and nuclear structure of $^{19}$F, DMTPC is mostly sensitive to spin-dependent WIMP coupling.
3. DMTPC m³ detector

The DMTPC collaboration is currently constructing a detector with a fiducial volume of 1 m³, 50 times that of its predecessor. A schematic of the detector design is shown in Figure 2. The vacuum vessel has a capacity of 4.5 m³ and is outfitted with access ports on all sides for modular installation of services, such as pressure gauges, high-voltage electrical feedthroughs or the turbo-molecular pump, and readout components, such as CCD cameras or PMTs.

![Figure 2. A schematic of the DMTPC m³ detector.](image)

3.1. Internal design

The current design of the m³ detector features two sets of back-to-back TPCs, each of which share a single amplification region and corresponding readout components. By separating the total drift volume into four independent regions, each 275 mm long, the maximum diffusion experienced by a track is constrained to < 2 mm, preventing further degradation of the directional performance of the detector due to the scale-up in volume. In addition, the lower operating pressure of 30 Torr with respect to previous prototypes increases the average track length and further reduces the effect of diffusion. Design considerations such as these will aid in scaling the technology to the exposure necessary for identifying a signal coming from dark matter. The compact and modular design of the m³ detector can be replicated in order to achieve a ton-scale target mass.

3.2. TPC design

Each TPC consists of a cathode, field cage and amplification region with one ground plane and one anode plane, shared between a pair of back-to-back TPCs. All components have been re-designed with respect to previous prototypes to account for the scale-up in volume and new horizontal orientation. The cathode has been designed to utilize the maximum width of available wire mesh (48") and not restrict the camera field of view. The field cage has been designed to minimize a) surface area and surface-level radioactive contaminants; b) the acceptance of particles (namely, radon daughter decays) originating outside the fiducial volume; and c) electric field non-uniformity. The amplification region is now segmented both mechanically and electrically into four equally-sized quadrants in order to reduce the capacitance of each of the readout channels. A single support frame holds a ‘triple-mesh’ amplification region together, comprised of one anode plane (four quadrants) sandwiched between two ground planes (eight quadrants) 1.0 ± 0.1 mm apart. The capacitance of a single quadrant is 2.2 ± 0.2 nF.
Precautions have been taken to reduce the largest source of background in the detector, coming from radioactivity of the internal components. Various materials were assayed for U, Th and Rn content and only low-background, radiopure materials were selected for construction. The field cage rings are made from high-purity, oxygen-free copper C10100. The cathode and anode meshes are woven from $\varnothing 30.5 \mu m$ SS-316 threads, with 50 LPI (88% transparency) and 100 LPI (79% transparency), respectively. Mechanical support parts are made from delrin to avoid electrical discharge to e.g. the walls of the vacuum vessel. Radon emanation assays of stock delrin measure $1 - 2^{+6}_{-2}$ atoms/m$^2$/hour.

Detailed two-dimensional electric field simulation studies were performed in order to optimize the ratio of fiducial volume to surface area of the inner field cage system. In comparison with the 10-L prototype, the fiducial volume of the m$^3$ detector has increased by a factor of 100, while the surface area of the field cage system has increased by only a factor of 2.5.

3.3. Readout components

Each pair of back-to-back TPCs is read out by one set of CCD camera(s) and PMT(s) installed opposite the amplification region. The left pair (see Figure 2), referred to as the ‘4-shooter’ side, is read out by four ProLine 9000 CCD cameras, with a front-illuminated 3056 x 3056 Kodak KAF-9000 sensor with 12 $\mu m$ x 12 $\mu m$ pixels, and one Hamamatsu R1408 PMT. The right pair, referred to as the ‘1-shooter’ side, is read out by a Spectral Instruments 1100S CCD camera, with a back-illuminated 4096 x 4096 Fairchild 486 sensor with 15 $\mu m$ x 15 $\mu m$ pixels, and four Hamamatsu R1408 PMTs. The ‘1-shooter’ and ‘4-shooter’ sides are different in order to assess the signal-to-noise and cost-effectiveness of each of the designs. All optical readout systems are external to the vacuum vessel, minimizing the amount of wetted materials inside the active volume.

In addition to optical readout systems, the ground planes of each of the amplification regions are read out via CAEN A1423 wideband amplifiers. Anode planes are read out via CREMAT CR-11X charge-sensitive pre-amplifiers. Signals from all charge readout channels and the PMTs are sent to two CAEN N6730 waveform digitizers.

3.4. Status and calibration

One out of four TPCs has been installed into the m$^3$ detector and commissioning studies are in progress. Figure 3 (left) shows a CCD image (‘4-shooter’ side) of a candidate nuclear recoil event from an AmBe source positioned below the detector and parallel to the amplification plane, at an operating pressure of 30 Torr, with cathode set to $-2730$ V and anode set to 730 V.

Figure 3. (left) CCD image of a candidate nuclear recoil event from an AmBe source, at 30 Torr operating pressure and anode set to 730 V. (right) Measured average gas gain from $^{55}$Fe calibration data as a function of anode set voltage, fit with an exponential.
The average gas (multiplication) gain at 30 Torr has been measured as a function of anode set voltage using the charge readout system described above and four 26 $\mu$Ci $^{55}$Fe sources installed inside the vacuum chamber behind the cathode. For a given anode set voltage, the pulse height spectrum of the corresponding anode readout channel is collected and fit with a gaussian plus an exponential to model the primary 5.9 keV $^{55}$Fe peak over background. The mean of the gaussian is then used to determine the average gas gain at the given anode set voltage. Figure 3 (right) shows the measured gas gain as a function of anode set voltage, for a constant anode-ground gap size of 1.0 mm.

4. Directional sensitivity
The projected directional sensitivity of the m$^3$ detector has been studied in [5], assuming the current TPC design, a fiducial volume of 1 m$^3$, an operating pressure of 30 Torr ($\sim$150 g target mass) and a gas gain of 100,000. A full simulation of the detector response was written and validated using data taken with previous detector prototypes and various radioactive sources, including $^{241}$Am, AmBe and deuterium-deuterium (DD). A directional sensitivity metric incorporating both vector (head-tail) and axial measurements was developed and the response to a source of WIMPs was simulated. Multiple sets of pseudo-experiments were run, each with $n$ signal events and assuming no background events, to determine the number of signal events needed to reject isotropy at the 0.1% level, shown in Figure 4.

![Acceptance Probabilities (p = 0.1%)](attachment:image.png)

**Figure 4.** Projected sensitivity of the DMTPC m$^3$ detector with 30 Torr CF$_4$, assuming a fiducial volume of 1 m$^3$ ($\sim$150 g target mass) and a gas gain of 100,000. A 50% best-quality cut has been applied here.

5. Conclusions
Commissioning of the first TPC of the DMTPC m$^3$ detector has begun and construction of the remaining three TPCs will continue in 2016. The directional performance of the detector will be studied on the surface before deployment underground at SNOLAB in late 2016 or early 2017. Assuming a fiducial volume of 1 m$^3$, a gas gain of 100,000, a target mass of 150 g (equivalent to 30 Torr of CF$_4$) and a WIMP-proton cross section of 1 fb, it would take 500 (300) m$^3$-years to acquire the necessary 450 signal events to reject isotropy half of the time at 3$\sigma$ significance for 100 (1000) GeV WIMPs.

References
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