

DMTPC: A dark matter detector with directional sensitivity

J.B.R. Battat*, S. Ahlen[†], T. Caldwell*, D. Dujmic*, A. Dushkin**, P. Fisher*, F. Golub**, S. Goyal**, S. Henderson*, A. Inglis[†], R. Lanza*, J. Lopez*, A. Kaboth*, G. Kohse*, J. Monroe*, G. Sciolla*, B.N. Skvorodnev**, H. Tomita[†], R. Vanderspek*, H. Wellenstein** and R. Yamamoto*

**Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

[†]*Boston University, Boston, MA, 02215, USA*

***Brandeis University, Waltham, MA, 02453, USA*

Abstract. By correlating nuclear recoil directions with the Earth's direction of motion through the Galaxy, a directional dark matter detector can unambiguously detect Weakly Interacting Massive Particles (WIMPs), even in the presence of backgrounds. Here, we describe the Dark Matter Time-Projection Chamber (DMTPC) detector, a TPC filled with CF₄ gas at low pressure (0.1 atm). Using this detector, we have measured the vector direction (head-tail) of nuclear recoils down to energies of 100 keV with an angular resolution of $\leq 15^\circ$. To study our detector backgrounds, we have operated in a basement laboratory on the MIT campus for several months. We are currently building a new, high-radiopurity detector for deployment underground at the Waste Isolation Pilot Plant facility in New Mexico.

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DIRECTIONAL DARK MATTER DETECTION

Astrophysical observations, coupled with simulations of galaxy formation, tell us that the baryonic disk of the Milky Way is likely embedded in a much larger halo of dark matter. The stars and gas are believed to rotate with respect to the halo. An Earth-bound observer, in orbit about the center of the Galaxy, will therefore move through the dark matter distribution and experience a head-wind of dark matter particles.

The smoking-gun signature of the above paradigm is an $O(1)$ daily modulation¹ in the direction of arrival of the dark matter wind at the Earth, due to the Earth's rotation [1]. For a detector at latitude $\sim 45^\circ$ (e.g. at MIT in Cambridge, MA), if the wind appears to come from the horizon at time t , then at $t + 12$ h, the wind will come from overhead.

The goal, then, of a directional detector is to reconstruct the time-dependent direction of the dark matter wind by measuring the recoil axis and direction of the recoiling nuclei. A large asymmetry in the direction of nuclear recoils with respect to the Galaxy would be the smoking gun for dark matter detection since no known background source can mimic

¹ Here, daily means sidereal day (with respect to distant stars), not solar day (with respect to the Sun).

this modulation signal. Here, we describe the Dark Matter Time-Projection Chamber (DMTPC) apparatus, a gas-based detector that is sensitive to the direction of the dark matter wind.

DETECTOR DESCRIPTION AND PERFORMANCE

The DMTPC detector, shown in Figure 1, is a dual, back-to-back, time-projection chamber (TPC) filled with CF_4 gas at low pressure (0.1 atm), with electronic and optical (CCD and PMT) readout. The active volume of the detector is 10 L, which, at 0.1 atm, corresponds to 3.3 g of CF_4 .

A recoiling nucleus from a dark matter interaction will ionize the gas along its track. The liberated electrons drift under a uniform electric field toward an amplification region. The 20 cm long drift region is established by the cathode at ~ -5 kV and the ground plane. These conductive planes are fine-woven meshes made from 28 μm wire with a 256 μm pitch. The amplification region consists of a copper-clad G10 anode at +0.7 kV separated from the ground plane by 500 μm . We achieve typical gas gains of 10^5 with minimal sparking. The mesh-based amplification region produces two-dimensional images of particle tracks.

The charge deposited on the anode, which is proportional to the total recoil energy, is recorded with a fast digitizer. The scintillation light from tracks is imaged with a CCD camera, providing a measurement of the total recoil energy, the energy loss per unit length dE/dx , and the length and shape of the 2-dimensional projection of the track. A photomultiplier tube (PMT) also detects the scintillation light. The timing profile of the PMT signal provides information about the third dimension (vertical extent) of the track. The combination of electronic and light readout ensures effective background discrimination.

The energy resolution of the charge readout is $\sim 10\%$ at 5.9 keV (measured with an ^{55}Fe source), and is $\sim 15\%$ at 50 keV for the CCD readout. The detector has excellent electron rejection (better than 10^6) owing to the low surface brightness and extensive length of electron tracks. Alpha tracks are distinguished from nuclear recoils by their energy-range relationship.

CF_4 GAS PROPERTIES

CF_4 is an excellent target gas for a dark matter detector. It provides strong sensitivity to spin-dependent interactions because of the unpaired proton in fluorine. It is also an efficient scintillator, with significant emission around 650 nm [3], which is well matched to the quantum efficiency of the ubiquitous silicon CCDs.

CF_4 also has very low electron diffusion. In order to faithfully reconstruct a recoil track, the transverse electron diffusion must not exceed the recoil track length. Typical WIMP-induced recoils in our detector extend 1–3 millimeters. Recent measurements by our group have shown that we can drift electrons over 20 cm with less than 1 mm of transverse diffusion [4].

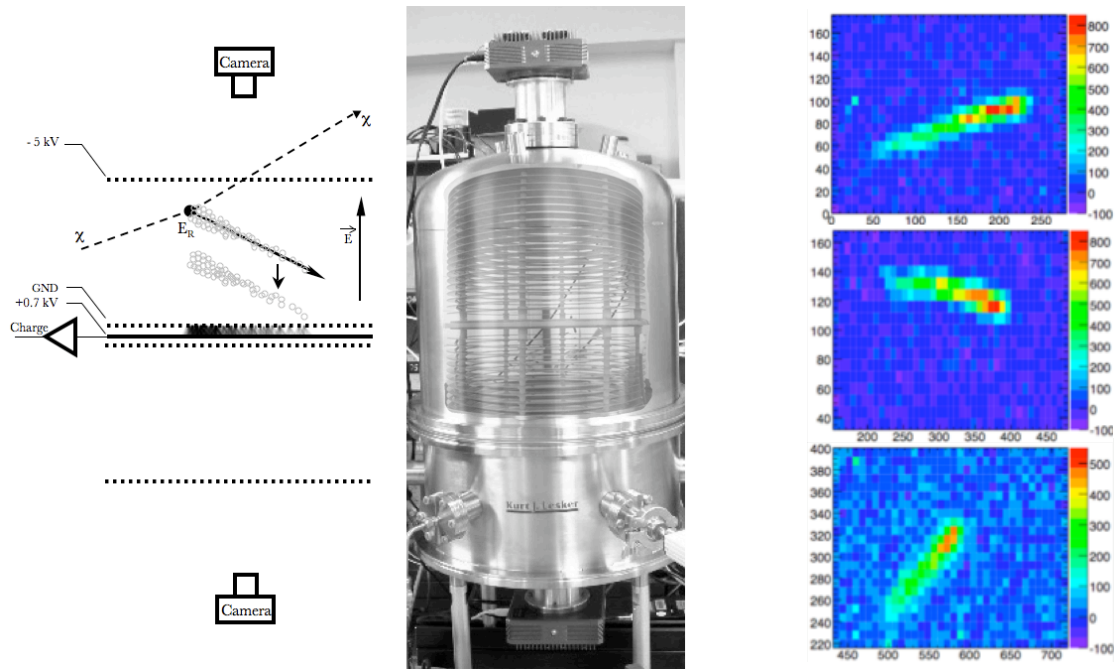


FIGURE 1. (left) Schematic of a WIMP-nucleus interaction in one side of the dual TPC. (center) Photograph of the DMTPC 10L detector with an image of the field cage overlaid to provide an artificial glimpse inside the vacuum vessel. (right) CCD images of ^{252}Cf neutron-induced nuclear recoils [2].

HEAD-TAIL MEASUREMENTS FOR NUCLEAR RECOILS

The angular distribution of WIMP-induced fluorine nuclei recoils is similar to those induced by ^{252}Cf neutrons. With 75 torr of CF_4 in the TPC, we used a ^{252}Cf neutron source to calibrate the sensitivity of our detector and analysis software to WIMP events [2]. Sample images of nuclear recoil candidate events are shown in Figure 1. The recoil axis is manifest in the track topology, and the vector direction of the recoil (the head-tail effect) is clearly determined from the light distribution along the track: higher light intensity marks the start of the recoil. It is readily apparent from the ensemble of images that the ^{252}Cf neutrons were incident from the right.

A plot of the observed range vs. energy for candidate nuclear recoil events is shown in Figure 2. The observations agree very closely with our Monte Carlo studies. We quantify our ability to reconstruct the head-tail of nuclear recoils with a “skewness” parameter $S = \mu_3/\mu_2^{3/2}$, where μ_2 and μ_3 are the second and third moments, respectively, of the light distribution along the track. For the neutron calibration run, kinematic constraints require that S be negative. Figure 2 shows that we successfully reconstruct the head-tail for nuclear recoils down to 100 keV. Furthermore, Monte Carlo studies show that we reconstruct the nuclear recoil direction with an angular resolution of 15° at 100 keV, improving to 10° at 300 keV (Figure 2).

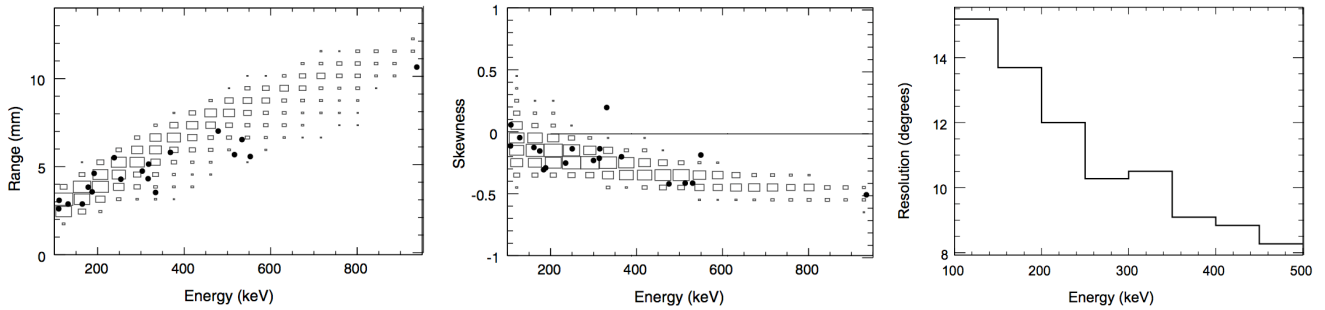


FIGURE 2. (*left*) The range vs. energy for candidate nuclear recoils (points) and the Monte Carlo prediction (box histogram). (*center*) The skewness parameter S vs. energy for data and Monte Carlo. We can correctly determine the head-tail down to 100 keV. (*right*) Monte Carlo study of the angular resolution of the track reconstruction. Images taken from [2].

CURRENT AND FUTURE PLANS

The 10L DMTPC detector was run in a basement laboratory on the MIT campus for nine weeks to study the detector backgrounds. The chamber was refilled with CF_4 gas each day to ensure a gain stability of 1%. An analysis of the data from this surface run will be the subject of a forthcoming publication.

We are currently constructing a second detector to deploy underground at the Waste Isolation Pilot Plant (WIPP). At WIPP (1.6 km.w.e.), we expect much less than one neutron-induced background per year in our detector. In addition, careful attention to material radiopurity and environmental radon levels during assembly should strongly suppress the alpha backgrounds.

Meanwhile, we are also designing a cubic meter detector comprised of four TPC volumes and transparent mesh anodes. At 75 torr, the cubic meter detector would contain 0.38 kg of target material. With three months of live time (exposure ~ 0.1 kg yr), this detector is capable of setting leading constraints on spin-dependent WIMP-proton interactions [2].

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