Results from DMTPC 10-liter Detector

D. Dujmic, J. Battat, T. Caldwell, L. Fedus, P. Fisher, S. Henderson, R. Lanza, A. Lee, J. Lopez, A. Kaboth, G. Kohse, J. Monroe, R. Vanderspek, T. Sahin, G. Sciolla, I. Wolf, R. Yamamoto, H. Yegorian
Massachusetts Institute of Technology, Cambridge, MA 02421, USA
S. Ahlen, A. Inglis, K. Otis, H. Tomita
Boston University, Boston, MA 02215, USA
H. Wellenstein
Brandeis University, Waltham, MA 02454, USA
E-mail: ddujmic@mit.edu

Abstract. The known direction of motion of dark matter particles relative to the Earth may be an ambiguous identification even in the presence of backgrounds. A directional-sensitive detector prototype using a low-density CF$_4$ gas with a 10 liter fiducial volume is operated for several weeks in a basement laboratory. We present initial results that confirm good detector performance and set preliminary limits on spin-dependent dark matter interactions.

1. Introduction

Observation of weakly interacting massive particles (WIMPs) may require a good background rejection and a correlation of the WIMP direction with the galactic motion through the dark matter halo [1]. Both requirements can be accomplished with detectors using low-pressure gas as the target material. However, the low density of gaseous detectors requires large detector volumes with fine granularity. We address this challenge by building a dark matter time-projection chamber (DMTPC) with optical readout that allows good sensitivity to WIMP-induced signals and is scalable to larger volumes.

2. DMTPC-10L Detector

A schematic of the DMTPC detector is shown in Figure 1. A stainless steel vessel is filled with 75 Torr of CF$_4$ gas and holds two back-to-back time-projection-chambers (TPC). Ionization electrons created by a recoiling nucleus are drifted in an electric field ($\sim 250$ V/cm) toward the amplification region for detection. Each drift cage is made of stainless steel rings with the inner diameter of 25 cm and a total height of 25 cm. Attenuation of primary ionization electrons due to attachment to CF$_4$ gas molecules is measured to be consistent with zero.

The amplification region uses a solid copper for the anode and a stainless steel mesh with 256 $\mu$m pitch as the grounded electrode. A detailed description and performance evaluation of such amplification system is given in Ref. [2]. The charge gain in the detector at 75 Torr is around $10^5$ with a spark rate less than 10 mHz for the nominal anode voltage (720 V). Scintillation photons created during the avalanche charge multiplication (see [3]) are collected by a Nikon photographic lens with f-stop ratio of 1.2 and focal distance of 55 mm, and are...
Figure 1. A vacuum vessel holding a double-sided TPC with 10-liter fiducial volume, and a calculation of field uniformity \( (|E_\parallel|/E_{\text{tot}}) \), with each color shade corresponding to 1% of the change in the field ratio. The enlarged section of the amplification is shown in the left, consisting of a grounded mesh and a solid copper anode separated by 0.5 mm fluorocarbon wires. The scintillation light is recorded by CCD cameras, and charge is read out from the anodes.

recorded with Apogee U6 cameras using a Kodak KAF-1001E CCD chip. The total area imaged by each CCD is \( 16 \times 16 \) cm\(^2\) so the total active volume is approximately 10 liters.

The energy resolution of the CCD readout is measured using segments of tracks from the \(^{241}\)Am source. The resolution is computed from the total light originating from the segment, and we find \( \sigma_E/E = 14\% \) at 80 keV. The resolution can be further improved with charge readout from the anode. This is confirmed using 5.9 keV line from \(^{55}\)Fe source to obtain the resolution of \( \sigma_E/E = 10\% \).

The spatial resolution in the CCD readout plane is measured using the transverse spread of tracks from \(^{241}\)Am source. The resolution is affected by the number of CCD pixels, \( n_{\text{bin}} \) merged into a readout bin (98\(\mu\)m \( \cdot \) \( n_{\text{bin}} \)), the spread of an electron avalanche in the amplification gap (\( \sim 80\mu\)m), and the mesh pitch (256\(\mu\)m/\( \sqrt{12} \) \( \sim \) 74\(\mu\)m). The measurement itself is affected by the imperfect collimation of the source (50\(\mu\)m) and the straggling of alpha particles through CF\(_4\) gas (40\(\mu\)m). However, the dominant contribution to the spatial resolution uncertainty comes from the electron diffusion \( (\sqrt{107 z_{\text{drift}}/E_{\text{drift}}} \, \mu\text{m}) \) where \( z_{\text{drift}} \) (cm) is the drift distance, and \( E_{\text{drift}} \) (V/cm) is the electric field.

3. Results from Surface Run
In order to evaluate the detector’s background and the stability, we take data in a basement laboratory for several weeks. The total mass in the fiducial volume is 3.3 g and the total live time is 11 days. Gas is replaced every 24 h and we measure stability in the detector gain and the spatial resolution to be better than 1%. We take 5 second exposures and record every event.

Dominant sources of background are alpha tracks originating from the detector surface (10 mHz) and interactions with the CCD chip, so called ‘worms’ (10 mHz). The alpha background is entering the CCD viewfield from the sides and can be eliminated by requiring that a track not cross the edge of CCD field of view. The alpha rate is constant and originates from radioactivity inside the detector. We reduced this rate by a factor of five by replacing the
stainless-steel rings of the drift cage with rings made of off-the-shelf copper.

The worms consist of two sources: x-rays from materials inside the CCD and cosmic-induced radiation. Most of these events can be eliminated with cuts on the energy and shape of CCD pixels, but hardware-based remedies are under study, too.

We observe 7 events after the analysis cuts. The length and energy of these events are consistent with nuclear recoils induced by neutron scattering (Figure 2, left). Our preliminary estimate for the number of expected recoils from cosmic-induced neutrons at the Earth’s surface is twice as high, but more detailed calculations taking into account overburden of the basement lab are under way. We compute the upper limit on the spin-dependent cross section (Figure 2, right) using the Feldman-Cousins method and standard assumptions about the dark matter halo [4].

4. Summary and Plans

A prototype detector with total fiducial volume of 10 liters and filled with low-pressure CF$_4$ gas has been built and operated for several weeks in a surface laboratory. We demonstrate excellent energy and spatial resolution in the detection of nuclear recoils. A preliminary analysis shows that the dominant background comes from alpha tracks inside the TPC materials and direct interactions with the CCD chip. These events can be eliminated with analysis cuts and the remaining background energy and range are consistent with interactions with cosmic-induced neutrons.

In order to improve the detector sensitivity and eliminate the neutron background we are making preparations for operation in an underground laboratory (WIPP). Completion of these tests will allow us to design a cubic-meter module that will be a building block of a large-scale detector.

5. Acknowledgments

We wish to thank the Office of Environment, Health & Safety and the Laboratory for Nuclear Science MIT for technical support. We acknowledge support by the Advanced Detector Research Program of the U.S. Department of Energy (contract number 6916448), the MIT Kavli Institute for Astrophysics and Space Research, and the Physics Department at MIT.

[1] D. N. Spergel, Phys. Rev. D 37, 1353 (1988);
[2] D. Dujmic et al., Astropart. Phys. 30 (2008) 58-64
[3] A. Kaboth et al., [DMTPC Collaboration] Nucl. Instrum. Meth. A 592, 63 (2008).
[4] J. D. Lewin and P. F. Smith, Astropart. Phys. 6, 87 (1996).