DMTPC-10L: Direction-Sensitive Dark Matter Detector Prototype

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The known direction of motion of dark matter particles relative to the Earth may be a key for their unambiguous identification even in the presence of backgrounds. We describe a prototype detector that is able to reconstruct direction vectors of weakly interacting massive particles that may the dominant constituent of the dark matter in our galaxy. The detector uses a low-density gas (CF$_4$) in a 10liter time-projection chamber with mesh-based electrodes and optical and charge readout. Initial results confirm good performance in the reconstruction of direction angle and sense ('head-tail') for low-momentum nuclear recoils.

I. 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. 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, and the shortness of signal tracks necessitate fine detector granularities. In the case of CF$_4$ as the detector material, one ton of gas occupies a volume of approximately $16 \times 16 \times 16$ m$^3$ at 50 Torr of pressure, and a 50 keV fluorine recoil travels 1.5 mm. Therefore, a multi-cubic meter detector with resolution of the order of hundreds of micrometers is needed for a directional dark matter experiment.

II. DMTPC-10L DETECTOR

A schematic of the DMTPC detector is shown in Figure[1] A stainless steel vessel is filled with 50-100 Torr of CF$_4$ gas and holds two back-to-back time-projection-chambers (TPC’s). Ionization electrons that are created by recoiling nucleus are drifted in an electric field ($\sim 400$ V/cm) toward the amplification region so they can be detected. Each drift cage is made of stainless steel rings with the inner diameter of 25 cm and a total height of 25 cm. The separation and the width of the rings are optimized using a calculation based on the finite elements method in order to achieve uniform electric field in the vertical direction with a minimum number of drift rings. The perpendicular (radial) component of the electric field is less than 1% in the entire fiducial volume. The height of the drift region is limited by the electron diffusion [1].

A double-sided amplification region uses a solid copper for the anode and a stainless steel mesh with 256 µm pitch as the grounded electrode. A detailed description and performance evaluation of such amplification system is given in Ref. [2]. Scintillation photons created during the avalanche charge multiplication are collected by Nikon photographic lens with f-stop ratio of 1.2 and focal distance of 55 mm, and are recorded with Apogee U6 cameras using a Kodak

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FIG. 1: Contours of a vacuum vessel holding a detector with 10-liter fiducial volume. The drift cage consists of stainless steel rings with 25 cm inner diameter. A calculation of field uniformity ($|E_\perp/E_{tot}|$) in the drift cage is superimposed to the drawing, with each color shade corresponding to 1% of the change in the normalized transverse field. The enlarged section of the amplification is shown on the left, with the field created in between a grounded mesh and a solid copper anode separated by 0.5 mm fluorocarbon wires. Two identical structures are used for the two drift regions. The scintillation light is recorded by two CCD cameras on top and bottom, and charge is read out of the two anodes.

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 avalanche creates approximately 3 electrons for each scintillation photon with the wavelength between 200-800 nm, or approximately an order of magnitude more electrons than photons in the wavelength range that is accessible to CCD detectors [3]. We use the charge readout to improve the energy resolution of low-momentum nuclear recoils. The signal is collected from the anode and passed through a charge-sensitive preamplifier (Ortec PC109) and shaping amplifier (Ortec 485) before being recorded with a digitizer (Tek 1002).

### III. CALIBRATION RESULTS

We demonstrate the ability to determine the directional sense of low-momentum recoils, the ‘head-tail’ effect, by exposing the detectors to neutrons from a $^{252}$Cf source. The ionization rate of a low-momentum nuclear recoil decreases as it slows down in the detector gas, and the sense of its direction can be deduced from the scintillation profile along the track. An image of the recoil track is shown in the left plot of Figure 2. Neutrons are incident from the right, and the nuclear recoil also propagates from the right, which is evident from a decreasing light intensity. The sense of direction in single events can be reconstructed down to approximately 100 keV of recoil energy [1], but a larger data sample is needed to determine the full potential of the detector.

In order to measure the energy resolution, we expose the detector to x-rays from $^{55}$Fe source. A histogram of amplitudes of signal pulses is shown in the right plot in Figure 3. The peak corresponds to 5.9 keV x-rays from K-α lines, and its width gives the energy resolution of approximately 19%.
FIG. 2: Detector response: A CCD image of nuclear recoil in exposure to neutrons from a $^{252}$Cf source (left), and a distribution of reconstructed angles with head-tail information in data and simulated samples (right).

FIG. 3: A histogram of charge peak heights in exposure to 5.9 x-rays from $^{55}$Fe source.

IV. SUMMARY AND PLANS

Directional detection of dark matter requires large detector volumes with fine granularities. We have built a prototype detector consisting of two TPC modules filled with low-pressure CF$_4$ gas, and demonstrated reconstruction of the directionality and directional sense. A detector system based on this technology can improve current limits on spin-dependent dark matter interactions with approximately 0.1 kg·y of CF$_4$ exposure, and test New Physics models with approximately 100 kg·y [4]. We are currently taking data with the 10-liter prototype at the surface laboratory, and making preparations for operation in an underground laboratory. Completion of these tests will allow us to design a cubic-meter module that will be a building block of a ton-scale detector.

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[1] D. Dujmic et al., Nucl. Instrum. Meth. A 584, 327 (2008).
[2] D. Dujmic et al., Astropart. Phys. 30 (2008) 58-64
[3] A. Kaboth et al., Nucl. Instrum. Meth. A 592 (2008) 63.
[4] G. Sciolla et al., these proceedings, arXiv:0810.0291 [astro-ph].