

DM-TPC: a new approach to directional detection of Dark Matter

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Directional detection can provide unambiguous observation of Dark Matter interactions even in presence of insidious backgrounds. The DM-TPC collaboration is developing a detector with the goal of measuring the direction and sense of nuclear recoils produced in Dark Matter interactions. The detector consists of a Time Projection Chamber with optical readout filled with CF₄ gas at low pressure. A collision between a WIMP and a gas molecule results in a nuclear recoil of 1-2 nm. The measurement of the energy loss along the recoil allows us to determine the sense and the direction of the recoil. Results from a prototype detector operated in a low-energy neutron beam clearly demonstrate the suitability of this approach to measure directionality. A full-scale module with an active volume of about one cubic meter is now being designed. This detector, which will be operated underground in 2009, will allow us to set competitive limits on spin-dependent Dark Matter interactions using a directional detector.

1 The need for a novel Dark Matter detector

Searches for non-baryonic Dark Matter (DM) in the form of Weakly Interacting Massive Particles (WIMPs) rely on detection of nuclear recoils created by the elastic scattering between a WIMP and the detector material. In presence of backgrounds, an unambiguous positive observation can be provided by detecting the direction of the incoming WIMP.¹ As the Earth moves in the galactic Dark Matter halo, the WIMPs appear to come at us with an average velocity of 220 km/s from the direction of the constellation Cygnus. Due to the relative orientation between the Earth's rotation axis and the direction of the Dark Matter wind, the direction of the WIMPs changes with respect to our detector on Earth by about 90 degrees every twelve hours. Since no background is expected to correlate with the position of Cygnus in the sky, directional detection will improve the sensitivity to Dark Matter by orders of magnitude.² If the detector is also able to determine the sense of the direction, the sensitivity to DM is further enhanced.² In addition to background rejection, the measurement of the direction of Dark Matter will also allow us to discriminate between various Dark Matter models.

Dark Matter particles can interact with ordinary matter via spin-independent (scalar) or spin-dependent (axial vector) interactions. Most of the current experiments concentrate on searches for scalar couplings and are able to place very stringent limits on spin-independent interactions excluding cross-sections above 10^{-43} cm².

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In contrast, the existing limits on axial-vector couplings are almost seven orders of magnitude less stringent. Despite the modest experimental effort in this sector, these interactions are interesting because they are expected to be enhanced with respect to the scalar interactions in theoretical models in which the Lightest Supersymmetric Particle has a substantial Higgsino contribution.³ Therefore there is an urgent need for improving the searches for spin-dependent interactions of Dark Matter. Materials rich in fluorine, with nuclear spin of 1/2, are the most suitable detector materials for such searches.⁴

2 The DM-TPC detector

The DM-TPC detector⁵ consists of a low pressure Time Projection Chamber (TPC) filled with tetra-fluoro-methane (CF_4). For a pressure inside the vessel of 50 torr, the typical collision of a WIMP with a gas molecule causes a nucleus to recoil by about 1 mm. The ionization electrons produced by the recoiling nucleus drift in the gas along a uniform electric field toward an amplification region created by two parallel woven meshes.⁶ The large electric fields present in this region cause the avalanche process, during which a substantial amount of scintillation light is produced.⁷ A CCD camera is used to detect such photons and to image the projection of the nucleus parallel to the amplification plane. The total amount of light deposited in the CCD measures the total energy of the recoil. Because the energy loss is not uniform along the trajectory, we can determine not only the direction of the incoming WIMP, but also its sense ("head-tail" measurement). A phototube provides a measurement of the recoil parallel to the drift direction and serves as a trigger for reading out the CCD camera.

The combination of the various measurements provided by this detector is very effective in suppressing backgrounds due to alpha particles, electrons, and photons. As an example, the rejection factor measured for photons is better than 2 parts per million.

The DM-TPC detector is designed with the goal of maturing into a large underground experiment. The choice of an optical readout is motivated by the modest cost-per-channel obtainable with the use of a CCD camera, making it possible in the future to economically scale the detector to large volumes. The choice of CF_4 gas as active material is motivated by the low transverse diffusion and good scintillation properties of this gas. In addition, CF_4 is non-toxic and non-flammable, making it easier to operate the detector underground. Finally, this gas contains four atoms of fluorine for each atom of carbon, making the DM-TPC detector ideal to study spin-dependent interactions.

3 Recent results

A small prototype of the DM-TPC detector, with an active volume of $10 \times 10 \times 2.6 \text{ cm}^3$, has been operational since Spring 2007. This chamber was built to demonstrate the validity of the detector technology. In particular, this prototype was used to prove that our technology can indeed determine the sense of the direction of low-energy nuclear recoils ("head-tail" effect).

The prototype was calibrated with 5.5 MeV alpha particles produced by a ^{241}Am source. The energy loss (dE/dx) for 5.5 MeV alpha particles in CF_4 was measured and compared with the MC simulation. The agreement between data and MC was found to be excellent. The same alpha source was also used to measure the resolution as a function of the drift distance of the primary electrons to study the effect of the diffusion. These measurements showed⁸ that the drift distance should be limited to 25 cm.

We have used this chamber to study the recoils of fluorine nuclei in interaction with low energy neutrons, which provide a signature very similar to that of a WIMP. For our tests we used a 14 MeV neutron source from a deuterium-tritium tube as well as a ^{252}Cf source. The energy of the reconstructed recoils was between 100 and 800 keV. Because of the small energy

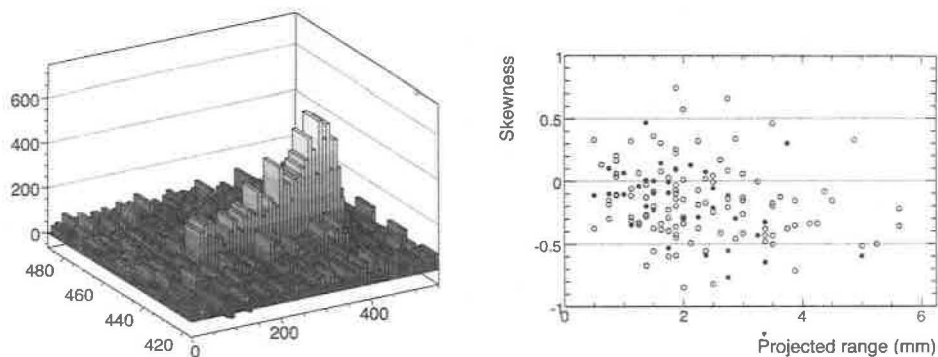


Figure 1: Left: dE/dx distribution for a fluorine nucleus recoiling with an energy of about 250 keV after being struck by a neutron. The direction of the incident neutron is right to left. The larger energy loss at the right of the track and lower energy loss at the left of the track is characteristics of the “head-tail” effect. Right: skewness of recoil events versus length of the recoil track, which is proportional to the recoil’s kinetic energy. Full (open) dots show data taken with the detector oriented parallel (anti-parallel) to the neutron flux.

of the recoiling nucleus, we expect the energy deposition to uniformly decrease along the path of the recoil, allowing us to identify the “head” (“tail”) of the event by a smaller (larger) energy deposition.

Figure 1 (left) shows the energy-loss per unit length (dE/dx) of one recoiling nucleus. The change of dE/dx along the recoil track is clearly visible. To quantify the “head-tail” effect we define the skewness as $\gamma \equiv \mu_3/\mu_2^{1.5}$, where μ_2 and μ_3 are the second and third moments of the energy deposit along the track, respectively. Figure 1 (right) shows skewness as a function of the length of the recoil track. For our setup, we expect negative skewness to dominate, which is clearly observed in the data. Averaging over all energies we determine that $(74 \pm 4)\%$ of the recoils have negative skewness. The effect is even more pronounced for events with energies above 500 keV. These results provided the first observation of the “head-tail” effect for low-energy nuclear recoils.⁵

The results described so far were obtained with the first generation DM-TPC prototype, which was using a wire-based amplification region and took data at pressure of 200 torr. These measurements have been repeated using an improved detector that uses a mesh-based amplification region. New data⁶ using nuclear recoils from a ^{252}Cf source and a pressure of 75 torr proved that our detector has good head-tail discrimination for recoils as low as 100 keV. The angular resolution for such recoils was measured to be better than 15 degrees. Figure 2 shows a typical nuclear recoil reconstructed in our detector using the mesh-based amplification technique.

4 Underground run with a larger detector

Given the promising results obtained by our R&D efforts, we decided to take this project to the next level and build a larger detector with an active volume of about one cubic meter. When operated at 50 torr, this device will have an active mass of 250 g. In one year of operation underground, such a detector will accumulate 90 kg-day of exposure. The successful operation of this detector will provide very competitive spin-dependent limits on Dark Matter cross-sections. If successful this effort will lay the foundation for a large (a few hundred kg) directional Dark Matter detector with substantial potential to directly observe Dark Matter and determine its direction. This experiment is an ideal fit for the Deep Underground Science and Engineering

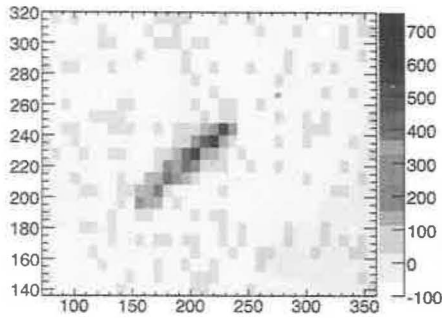


Figure 2: Scintillation profile of a typical nuclear recoil candidate in a ^{252}Cf run at 75 torr. The neutron was incident from the right (x axis) and the energy of the recoil shown was about 300 keV.

Laboratory (DUSEL) that is being planned in the Homestake mine in South Dakota.

5 Summary and conclusion

Directional detection may hold the key to unambiguous observation of Dark Matter in presence of backgrounds, and allows us to discriminate between models that predict Dark Matter to come from different directions in our galaxy.

The DM-TPC collaboration is developing a detector to achieve this goal. The device consists of a low-pressure TPC filled with CF_4 gas and read out by an array of CCD cameras. Our prototypes proved the detector concept and demonstrated its ability to reconstruct both the sense and direction of nuclear recoils above 100 keV. A larger detector is now being designed for underground operations in 2009 with the goal of obtaining competitive results on spin-dependent interactions using directional information. The success of this device will lay the foundation for a large Dark Matter experiment that will be able to detect the direction of WIMPs and discriminate between DM models in our galaxy.

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