DM-TPC: A DARK MATTER TIME PROJECTION CHAMBER

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The DM-TPC collaboration is developing an optical read-out time projection chamber for dark matter detection and identification. The detection material is low pressure CF4 gas, which has exceptional characteristics making it highly suitable for this purpose. Among these are excellent electron diffusion and scintillation performance, and the great sensitivity of fluorine to spin-dependent dark matter interactions. A summary of progress of the research and development program will be presented here.

1 An Imaging Time Projection Chamber

The concept of the Dark Matter Time Projection Chamber (DM-TPC) is illustrated in figure 1. The chamber contains CF4 gas at low pressure. An incoming dark matter particle collides elastically with an F nucleus, causing it to recoil with 10 to 100 keV of energy, with a range the order of one mm or more. The ionization electrons drift to the readout plane, where an electron avalanche occurs, accompanied by the emission of copious amounts of scintillation light. The scintillation light is imaged by the lens and CCD camera. Information on the component of the track perpendicular to the plane is provided by the time profile of a PMT signal recorded with a waveform digitizer. CF4 is an ideal gas due to its large scintillation efficiency and excellent electron diffusion characteristics. Furthermore, F has excellent properties for use in searches for dark matter through spin dependent interactions.
We have built two prototype detectors that have demonstrated this technique. An MIT prototype has used a readout plane consisting of a Multi-Wire-Proportional-Chamber (MWPC) to

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show that the direction of recoiling F nuclei can be determined. Examples of recoil tracks are shown in figure 2 for a CF4 pressure of 200 torr [1]. The recoils were produced by elastic collisions with neutrons, and extend down to energies of about 200 keV. Since the stopping power decreases as a particle's velocity approaches zero, the stopping end of the track is the one with reduced light yield. We expect that this effect will be observable below 100 keV when operated at lower pressure. Furthermore, we have recently developed a mesh readout plane that will also help with this goal. Tracks using the mesh in the MIT prototype are shown in figure 3. The stainless steel mesh, with wire diameter 30 μm and wire pitch 320 μm, was supported over a copper plate with spacers made of 300 μm plastic foil. With a CF4 pressure of 200 torr, the mesh operated with 2000 volts between the mesh and copper plate without sparking. The tracks shown in Figure 3 were produced by alpha particles. The Bragg peak from one alpha track is shown in figure 4. A second prototype has recently built at Boston University. This device has a 25 cm by 25 cm mesh and a cylindrical field cage 25 cm in diameter and 25 cm high.

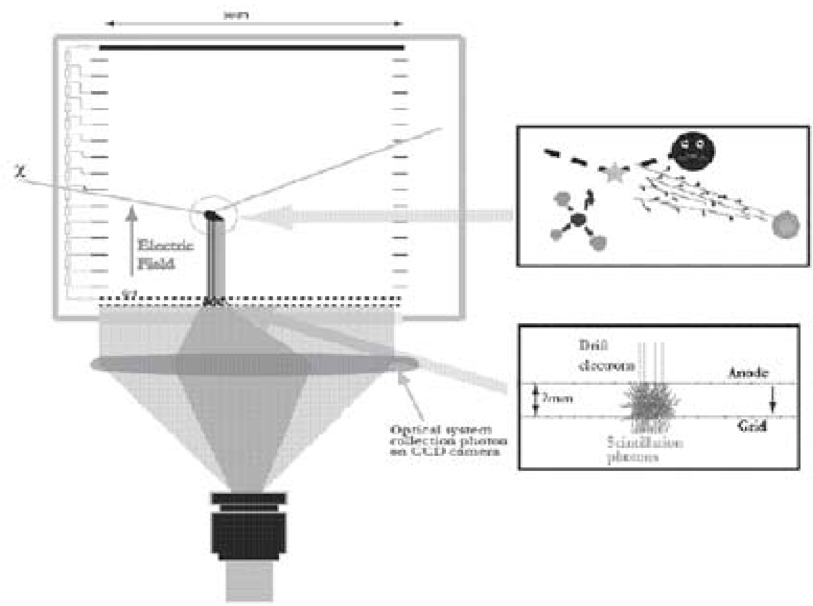

Figure 1: Schematic of DM-TPC.

2 Dark Matter Search via Spin-Dependent Interactions: Majorana Neutrinos

The latest cosmic microwave background results show that the matter content of the universe is 5.7 times larger than exists in the form of ordinary baryonic material [2]. Through observations of visible light, x-rays, and weak gravitational lensing of the collision of two clusters of galaxies, the dark matter has been found to interact very weakly, if at all, with itself and with ordinary matter by any means other than gravitation [3]. Many hypothetical particles have been advanced as candidates for dark matter. The list includes axions, the neutralino from supersymmetry, technibaryons, and massive fourth generation neutrinos from many models. Data on neutrino oscillations and direct limits on the mass of the electron neutrino from beta decay experiments have shown that the neutrinos from the first three generations are too light to provide the cold dark matter required for galaxy formation. LEP excludes fourth generation neutrinos with mass less than half the Z mass, and the first direct search for dark matter excluded massive Dirac neutrinos as the dark matter of our Galaxy for neutrino masses between 20 GeV and 2 TeV [4].

Massive Majorana neutrinos have not yet been excluded as the dark matter. We consider the search for these particles to illustrate the potential of the DM-TPC.

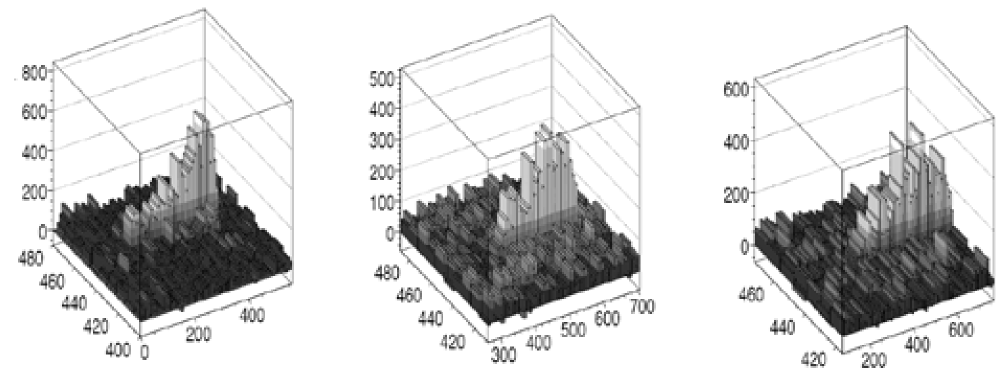

Figure 2: Tracks of recoiling F nuclei from collisions with neutrons. The neutrons came from the right. The direction of the neutron can be inferred from the track.

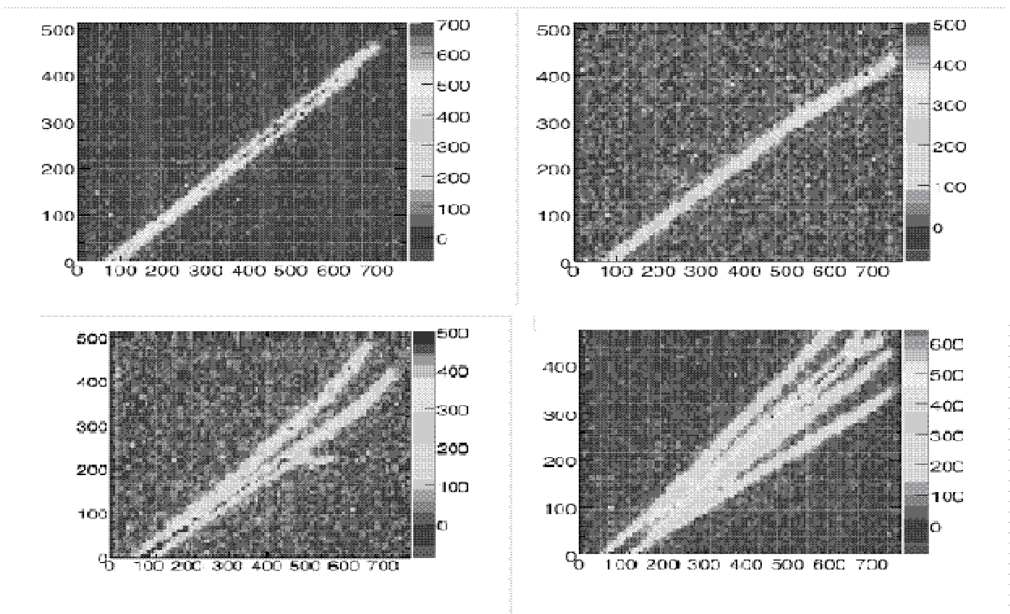

Figure 3: Alpha tracks from MIT prototype using mesh readout plane

Majorana neutrinos are predicted by numerous theories. They have been shown to be viable as dark matter in a minimal technicolor theory [5]. The authors of reference 5 have shown that the relic density of Majorana neutrinos can be in the observationally determined range if the Universe has a nonstandard history including an early dominance by a rolling scalar field as predicted by many models for dynamical dark energy. Majorana neutrinos also show up as Kaluza-Klein particles in a theory involving the universal extra dimension scenario [6]. Their collision cross section with nuclei is determined by their mass and the properties of the nuclei they interact with. The total cross section is $\sigma = \frac{2G_F^2\mu^2}{\pi\hbar^4}C^2\lambda^2 J(J+1)$, where μ is the reduced mass of the neutrino, J is the nuclear angular momentum quantum number of the nucleus, and $\lambda^2 J(J+1)$

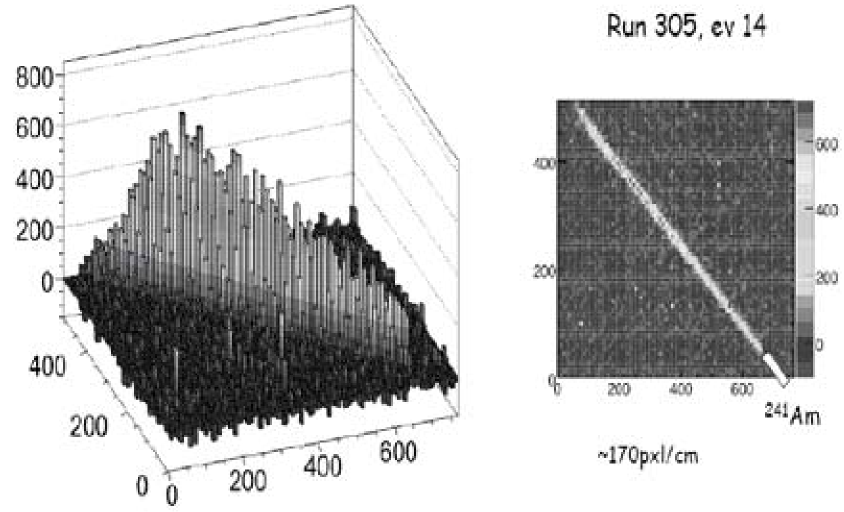

Figure 4: Bragg peak from alpha track using MIT prototype with mesh.

is the "spin-factor" of the nucleus. C is related to the quark spin content of the unpaired nucleon [7] and is 0.68 for the proton and -0.58 for the neutron. Estimates of the nuclear spin factor are given in reference 7 for a number of isotopes. The product of squared nucleus mass, isotopes per kg, and nuclear spin factor is a figure of merit as a Majorana neutrino detecting medium. This figure of merit is listed in parentheses (arbitrary units) for various promising nuclides: 1H (4.48), 19F (74.05), 23Na (5.68), 27Al (14.16), 43Ca (0.06), 73Ge (2.24), 93Nb (90.85), 127I (5.36), 129Xe (25.00), 131Xe (9.18). Form factor effects are difficult to calculate for spin-dependent interactions, but for F the effect [7] is less than 20% for recoil energies less than 100 keV. Thus it is seen that F provides the best return per kg of detector mass as any other detecting material. Leaving out the form factor correction term and assuming the neutrino mass is large compared to the F mass, the cross section for a Majorana neutrino with a fluorine nucleus is 3.1 pb. For a local dark matter density of 0.4 GeV/cm^3 there would be 300 interactions per year for 100 GeV neutrino mass in 1 kg of F. A few dozen of these would likely have recoil kinetic energies in excess of 100 keV, when one includes the effects of the tails of the neutrino velocity distribution. With our direction sensitive detector we can use the measured directions of the high energy recoils to test the hypothesis that they are produced in collisions with particles coming from the direction of the constellation Cygnus, which is believed to be the case for dark matter particles.

In the next year we plan to build a detector with a mass of 70 g of fluorine in a volume of 0.1 m^3 of CF4 at a gas pressure of 150 torr. The device will be operated at an appropriate underground site to reduce backgrounds from neutrons. The detector will have in a single vacuum vessel four cells, each of the order of 30 cm on a side based on diffusion and optical considerations. Each cell will be viewed by one CCD camera and two PMTs. This will permit 3-D track reconstruction and redundancy will enable the elimination of background events due to radioactivity events in the CCDs. The device would detect about one Majorana neutrino interaction per month if these particles are the dark matter.

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