Low Pressure Negative Ion Drift Chamber for Dark Matter Search

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Weakly Interacting Massive Particles (WIMPs) are an attractive candidate for the dark matter thought to make up the bulk of the mass of our universe. We explore here the possibility of using a low pressure negative ion drift chamber to search for WIMPs. The innovation of drifting ions, instead of electrons, allows the design of a detector with exceptional sensitivity to, background rejection from, and signature of WIMPs.

Since the earliest astrophysical measurements on galaxy clusters during the 1930’s an observational problem of dark mass has existed [1]. This problem persists to the present day in the most recent space based measurements on galaxy clusters [2]. In fact, the problem is present in practically every structure studied which is the size of a galaxy or larger [3]. Orbital velocities in large systems are systematically larger than they should be in the gravitational potential well of the visible mass in these systems. The discrepancies are not subtle. Even the lowest estimates imply that there is several times more dark gravitating material than there is visible matter [3]. The existence of dark matter is hardly in doubt; the question is, “What is it?”

The Big Bang theory of cosmology and the Standard Model of particle physics provide some clues. Big Bang nucleosynthesis calculations indicate that most of the dark matter must be non-baryonic [4]. When other arguments and data from cosmology and particle physics are included a general consensus in the field emerges that there are now 4 strong contenders: Massive Compact Halo Objects (MACHOs), neutrinos, axions and Weakly Interacting Massive Particles (WIMPs). Our concern here is with WIMP dark matter. Primack, Seckel, and Sadoulet [5] argued that if a stable WIMP exists in nature it must make up the dark matter. Supersymmetry provides a theoretical home [6] for WIMPs and the lightest-super-partner is stable in most theoretical schemes.

A considerable experimental effort to detect this attractive dark matter candidate has been mounted in the last two decades [7]. All direct searches for WIMPs utilize the same principle. WIMPs are detected by the recoiling ions they produce within a target material. The challenge is that the recoil energies (∼1 keV/amu) and interaction rates (< 1 (kg-day)^−1) are both small. A close look at the DAMA experiment [8] is illustrative of the search for dark matter today. First, the “no counts” limit, 5×10^−4 (kg-day)^−1(defined as 2.3 counts divided by the exposure in kg-days) is several orders of magnitude smaller than the published limit of 13 (kg-day)^−1. In other words, DAMA is currently background limited. In fact all currently running dark matter experiments are limited not by exposure (mass×time) but by background levels in the detectors. Since background, not exposure, is the limiting factor, most experiments utilize some form of event discrimination to reduce the integral background (IBG) to some lower accepted background (ABG). DAMA uses pulse shape discrimination to lower the ABG to ∼1/3.5 of the IBG, yielding the above limit. In the presence of non-zero ABG the only way to detect WIMPs is to look for some signature of WIMPs in the data. Without the ability to sense the direction of the recoil (extremely difficult in solids and liquids where the range is of order 100 Å) the only available signature is a small annual modulation of the total rate and energy spectrum [8]. Currently the DAMA collaboration claims to have found such a modulation in their data [9]. The lessons to be drawn from this discussion are as follows. First, large mass detectors are not at present an absolute requirement for improving limits because background, not exposure, still dominates the best experiments. Second, background rejection factors play a large role in current limits. And finally the presence of non-zero ABG leads to a desire for for a strong signature. We are proposing to build a detector which directly addresses this current experimental situation.

The detector will be a low pressure TPC filled with a mixture of target gas and an electronegative gas. The use of electronegative gas permits the chamber to operate in a new mode creating a Negative Ion Drift Chamber (NIDC). In a NIDC primary ionization electrons must be rapidly and efficiently captured by the electronegative gas molecules. The resulting negative ions drift to the anode. In the strong, inhomogeneous field near the anode wires the ions must be field ionized so that avalanche multiplication can occur. This last characteristic restricts the possible electronegative gases that can be used. Single-wire proportional counters using negative ion drift were previously used by one group [10] and gas detectors have been considered for dark matter searches before [11]. The innovation here
is that we realized and have verified experimentally that a NIDC has a number of specific advantages when applied to the search for dark matter.

The *raison d’etre* of a gaseous dark matter detector is its ability to measure components of the range of a WIMP-recoil. The NIDC concept greatly helps in this regard. Because ions drift, instead of electrons, transverse and longitudinal diffusion are suppressed to thermal levels, $0.72\text{mm} \sqrt{(E/1\text{m}) \times (1\text{kVcm}^{-1}/E)}$. No magnetic field is needed to suppress diffusion making the detector easily scalable. Standard methods of measuring the components of the range parallel to the anode plane can be utilized. The slow ion drift allows the track length projection in the drift direction to be measured with high resolution, even for very short tracks.

Several prototype NIDCs have been built and successfully operated in our labs using CS$_2$ as the electronegative component. Data have been taken with a variety of low pressure Ar:CS$_2$ and Xe:CS$_2$ gas mixtures. These chambers run stably with drift fields at least as high as 3200 V/cm at 40 Torr. The capture distance for ionization electrons has been measured to be a few tenths of a millimeter at 40 Torr, and the lateral and longitudinal diffusion of CS$_2^-$ at the thermal limit has been experimentally confirmed. The NIDC concept works.

The active volume of the first Directional Recoil Identification From Tracks (DRIFT) detector will be $\sim 1 \text{ m}^3$ in the form of two back-to-back TPCs sharing a common cathode within a cylindrical vacuum vessel. The gain structure will be a multiwire proportional chamber (MWPC) with 20(100)$\mu$m anode(grid) wires spaced at 1 mm. MSGD devices with back-side PGA output connection have also been considered. The fiducial region for WIMP recoil events is the volume between the cathode and the grid wires. The grid will be segmented with an annulus around the edge to veto ionizing radiation entering from the sides. Ionizing radiation entering from the top and bottom has to pass through the MWPCs where it produces a characteristic fast pulse shape (due to the high electric fields there) and can therefore also be vetoed.

To determine the sensitivity of the DRIFT detector a Monte Carlo simulation was run in which WIMP-Ar scattering events were generated in pure Ar. We do not intended to run DRIFT with a pure Ar fill. Ar is radioactive, it is unquenched, it is not electronegative, its atomic number is not high enough to make it a good WIMP scattering target, and it has no spin. However, the range and ionization of low energy ions in pure Ar are known. The measurement of these quantities for more palatable gas mixtures is a high priority for the DRIFT collaboration. Until then we will use Ar as illustrative of the DRIFT concept. The gas pressure must be kept low, we will use 40 Torr, in order that the range of a typical WIMP recoil is long enough to be measured using anodes spaced at 1 mm. The number of Ar recoils in the $1 \text{ m}^3$ DRIFT detector run for one year with energy greater than 40 keV was calculated as a function of WIMP mass. A plot of the resulting sensitivity is shown in Figure 1. The curves shown are the upper limits on the WIMP-nucleon (spin-independent) scattering cross section that could be set if no nuclear recoils were detected in one year. Note that the limit from running the DRIFT detector for one year with 40 Torr Ar would be roughly $\times 5$ stronger than the current DAMA limits for large mass WIMPs even though the mass of Ar in DRIFT is only 0.094 kg. The DRIFT limit would continue to improve as $1/t$ until the exposure reached the order of 1/ABG. This discussion shows that high sensitivity can be achieved with a very low target mass if the backgrounds can be sufficiently reduced.

Experience has shown that it is practically impossible to keep all background radiation out of the detector volume. The only real hope for achieving the sensitivity indicated above is to reject those events which do occur. DRIFT has very strong background rejection capabilities because of its ability to measure several, if not all, components of the range event-by-event.

The ~MeV alpha particles from radioactive decay of U and Th pose a serious background problem for DRIFT. Alpha’s which enter the fiducial volume from the sides will be vetoed as discussed above. Alphas from the grid wires or cathode which enter the fiducial volume, however, cannot be vetoed in this way. In addition because the grid wires and cathode are thick relative to the range of the alpha particles some of the alphas will emerge with energies small enough to produce ionization equivalent to WIMP events. The residual range of these particles, however, will be vastly different from that of WIMP recoils depositing the same total ionization. In 40 Torr Ar a 40 keV Ar recoil produces 500 primary ion pairs and has a projected range of 2.7 mm. In contrast an alpha-particle which produces 500 primary ionizations (15 keV) has a projected range of about 17 mm. Measuring the range is a powerful discriminant! The situation gets complicated when one realizes that alphas do not travel in straight lines, see Figure 2. The Ar recoil and alpha tracks shown in this figure were generated with the SRIM97 Monte Carlo scaled to match experimental data. Cuts on just two components of the range indicate the an alpha mis-identification probability (MIP) less than 5%. More sophisticated cuts or measurements of the third dimension will allow for even better alpha rejection.

For the Compton events generated by photons interacting within its fiducial volume or betas which enter the fiducial volume from the grid wires or the cathode the DRIFT detector has an even lower MIP. A 13 keV electron will give 500 primary ionizations in Ar but will travel $\sim 85 \text{ mm}$. As with alphas, the electrons don’t travel in straight lines, see Figure 3. The electrons in this figure were generated using the EGS/PRESTA simulation code. Cuts on just two components of the range indicate an electron MIP less than $3 \times 10^{-5}$. Again more sophisticated cuts or
measurements of the third dimension will allow for even better electron rejection. Experimentally we have measured a mis-identification probability less than 0.001 using $^{55}$Fe (6 keV) X-rays.

There is no rejection factor for neutrons as the recoils they produce are almost identical to those produced by WIMPs. The only hope for seeing one or less neutron recoils per year in DRIFT is to insure adequate shielding.

With the above electron and alpha MIPs in hand we can estimate the ABG in DRIFT after one year of running. For alphas the most important consideration is the radiopurity of the wires and the cathode. Commercially available stainless steel wires have been tested with U and Th concentration less than 0.5 ppb [22]. Acrylic to form the central cathode can be had with U and Th contamination less than 0.01 ppb [22]. The upper limits on the the radiopurity of the these elements and the MIP for alphas give an upper limit of the order of 10 events per year from alpha background in DRIFT. For the case that the actual levels are comparable to this limit, further highly effective reduction strategies are under study. The most promising is to measure the time difference between the arrival of the $\text{CS}_2^-$ ions at the anode and the arrival of the $\text{CS}_2^+$ ions at the cathode [22]. This will allow events to be localized in the gas away from the wires and cathode.

Events mis-identified as WIMP recoils can also arise from low energy Compton electrons from gammas which leak through the shield or are generated by the shield or detector materials, or from beta decays in the wires and gas. Using published flux measurements of gammas inside operating dark matter shields [15] and measurements of beta and gamma emitters in various construction materials we have been able to estimate the IBG from these sources. The $3 \times 10^{-5}$ upper limit on the MIP for low energy electrons means that the ABG from electrons will be less than 0.03 events per year.

There is no rejection factor for neutrons but by going underground the number of expected neutron recoils can be reduced to levels far below 1 event per year [14]. In summary there is every expectation that DRIFT will achieve the “zero-background” sensitivity discussed above. “What if we see something consistent with a WIMP recoil?”

In addition to having good sensitivity, the DRIFT detector also has a very robust signature for detecting WIMPs. WIMP signatures in direct detection experiments arise from the fact that the solar system rotates around the center of the Galaxy, through a halo of WIMPS generally believed to be nonrotating. WIMP velocities relative to the Earth are therefore a combination of the WIMP’s own Maxwellian, isotropic velocity distribution in the galactic potential well plus a uniform velocity (approximately equal in magnitude to the rms WIMP speed) due to the Solar System’s rotation around the center of the Galaxy. This motion (R.A. 21hr 12.0’, Dec. +48.19’’) is roughly toward the constellation Cygnus so colloquially one can say there is a WIMP “wind” blowing at the Earth from the direction of Cygnus.

Dark matter detectors which only measure energy deposition can take advantage of this asymmetric velocity distribution in the following way. From April-September the Earth’s velocity vector around the Sun has a component which is “into the wind” causing higher energy recoils at a higher rate in the detector. During the months October-March the opposite occurs. For a threshold energy of the recoil, $E_{th} = 0$ keV this asymmetry (difference divided by the sum) is 2% while for $E_{th} = \frac{1}{2} \text{keV/amu}$ A it rises to 5% [1].

Direction-sensitive experiments, like DRIFT, give a much stronger signature associated with the WIMP wind directional asymmetry. Consider a drift chamber located at North latitude equal to the declination of Cygnus. Over a sidereal day the direction of the WIMP “wind” relative to the anode plane changes from normal ($\tau_{cyg} = 90^\circ$) to parallel ($\tau_{cyg} \approx 0^\circ$). By measuring two components of the recoiling atom’s range, $\Delta x$ and $\Delta z$ the projected angle $\tau_{recoil}$ can be calculated for each event. We have extended the work of Spergel [9] by performing a Monte Carlo simulation of the recoils produced from 100 GeV WIMPs in 40 Torr Ar, including SRIM-generated scattering of the Ar recoils and drift diffusion. The simulation shows that $\Delta \tau = |\tau_{recoil} - \tau_{cyg} |$ has an asymmetric distribution peaked near 0°. An asymmetry is formed by counting recoils with $\Delta \tau$ less than 45° and greater than 45°. For $E_{th} = 0$ keV this asymmetry is 7% while for $E_{th} = \frac{1}{2} \text{keV/amu}$ A it rises to 17%. Much larger asymmetries, approaching 1, can be had if the start of the track can be distinguished from the end of the track. This is certainly possible in principle since the ionization per unit length does change over the length of the track.

Even without “head-tail” discrimination, this sidereal day asymmetry provides a very robust signature. There are several reasons for this. In any experiment seeking an effect through detection of an asymmetry the figure of merit (FOM) to achieve any given confidence level of detection is proportional to $FOM \propto a^2 N_{WIMP}(1 + \frac{N_{background}}{N_{WIMP}})$ where $N_{WIMP}$ is the number of WIMP events detected and $N_{background}$ is the number of background events detected. Clearly large mass detectors run for long times are desirable since this increases $N_{WIMP}$. This is the approach taken by groups using very large detector masses and seeking annual modulation. But this expression also shows that large asymmetries ($a^2$ dependence) and low backgrounds contribute strongly to the FOM. As an illustration of how powerful these considerations can be consider the DAMA report [8]. DAMA reports a signal consistent, at the 90% confidence level, with detection of an annual modulation. In the energy range 2–12 keV, the modulation reported is $0.037 \pm 0.008$ counts/day/kg/keV. This implies $85,000$ WIMP events are in the data sample. A DRIFT detector with an asymmetry of 17%, instead of 2%, and zero background could reach the same FOM level with only
70 WIMP events, i.e. with \( \approx 1000 \) times less exposure. In addition a sidereal-rate modulation rapidly goes out of synch with the solar day/night cycle and the short period imposes less stringent requirements on long term stability of the experiment.

For all of the reasons discussed above we feel that DRIFT is a powerful detector capable of making a significant contribution to cosmology and particle physics.

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![Graph](https://via.placeholder.com/150)

**FIG. 1.** Upper limits (90% c.l.) on the spin independent WIMP-nucleon interaction cross section obtained by the DAMA collaboration in comparison to the sensitivity of DRIFT after one year of running. Halo parameters and coherence parameterizations were identical. The DRIFT threshold for this calculation was 40 keV.
FIG. 2. The figures above show, from left to right, 40 keV Argon recoils, 15 keV alphas and 13 keV electrons in 40 Torr Ar.