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Low pressure negative ion time projection 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 time projection chamber to search for WIMPs. The innovation of drifting ions, instead of electrons, allows the design of a detector with very high sensitivity and background rejection and a robust statistical signature for WIMP interactions.

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I. INTRODUCTION

Since the earliest astrophysical measurements on galaxy clusters during the 1930s 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 focus of current research has shifted from determining the existence of dark matter to determining its makeup.

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 dark matter candidates [5]: massive compact halo objects (MACHOs), neutrinos, axions and weakly interacting massive particles (WIMPs). This article concerns a search for WIMP dark matter. Strong theoretical suggestions that the dark matter may be in this form include the argument of Primack, Seckel, and Sadoulet [6] that if a stable WIMP exists in nature it *must* make up the dark matter, and the naturalness of a stable, WIMP-like lightest-super-partner in supersymmetry [7] theories.

A considerable experimental effort to detect WIMP dark matter has been mounted in the last two decades [7]. All direct searches for WIMPs utilize the same principle. WIMPs are sought by operating low-background detectors sensitive to the recoiling ions the WIMPs would produce by elastic scattering within a target material. Such experiments are challenging because they must be sensitive enough to detect or place limits on WIMP interactions at the expected small interaction rates [<1 $(\mathrm{kg \cdot day})^{-1}$) and low recoil energies (~ 1 keV/amu).

II. CURRENT EXPERIMENTAL SITUATION

The experiment reported in Ref. [8] (DAMA) may be considered illustrative of current searches. In that work, the ''no counts'' limit, 5×10^{-4} $(\mathrm{kg \cdot day})^{-1}$(defined as 2.3 counts divided by the exposure in kg-days) is many orders of magnitude smaller than the published limit of 13 $(\mathrm{kg \cdot day})^{-1}$. In other words, Ref. [8] is currently background limited. *In fact all current 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). In Ref. [8] pulse shape discrimination is used to lower the ABG to $\sim$1/3.5 of the IBG, yielding the above limit.

In the (inevitable) presence of non-zero ABG, a positive WIMP signal could only be *detected* if some signature (usually statistical) specific to WIMP interactions were identified in the data. Without the ability to sense the direction of the recoil (barely possible [9] 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 [10]. Currently the authors of Ref. [8] do claim to have found such a modulation in their data.

The above discussion leads to the following conclusions. 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 is crucial for improvement of current limits. Finally, at a given ABG level the *detection* limit will be determined by the (statistical) strength of the WIMP signature. The detector proposed here is designed to obtain improved limits or confirmed detection by directly addressing these factors.

III. DETECTOR CONCEPT AND TESTS

The proposed detector is a low pressure time projection chamber (TPC) filled with a mixture of target gas and an electronegative gas. Low pressure operation (10–40 Torr) is dictated by an optimization calculation [11] based on expected WIMP characteristics, range-energy relations in gases, and achievable spatial resolution. A gaseous dark matter detector is unique in permitting components of the range of each candidate WIMP recoil to be measured, along with the total ionization produced in the gas. Powerful range-energy background rejection can therefore be employed. The use of electronegative gas permits the chamber to operate in a new mode which we call a negative ion time projection chamber (NITPC). For practical reasons, the NITPC concept is the key to achieving a gaseous dark matter detector with useful range-energy discrimination.

Primary ionization electrons in an NITPC are 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 [12] and gas detectors have been considered for dark matter searches before [13]. The innovation here is that we realized and have verified experimentally that a NITPC has a number of specific advantages when applied to the search for dark matter.

Unlike electrons, drifting ions remain in or near thermal equilibrium with the gas up to extremely high drift fields. Transverse *and* longitudinal diffusion are therefore suppressed to thermal levels,

$$\sigma_{\mathrm{diff}} \sim 0.72\,\mathrm{mm}\ \sqrt{(L/1\,\mathrm{m})\times(1\ \mathrm{kVcm}^{-1}/E)}.$$

It is important to note that we have experimentally verified this diffusion suppression up to very high E/P (see below). This eliminates the need for an applied magnetic field to reduce diffusion, making the detector size easily scalable. Furthermore the slow ion drift allows the track length projection along the drift direction to be measured with high resolution, even for very short tracks. Standard methods of measuring track length projections parallel to the anode plane are utilized. Thus the detector can be used to measure the recoil track orientation, leading to a robust WIMP detection signature discussed below. The power of tracking capability in limiting or identifying a WIMP signal has led us to name the NITPC dark matter program ‘‘DRIFT,’’ for directional recoil identification from tracks.

We have operated several prototype NITPCs in our labs using pure CS_2as the electronegative component, as well as low pressure Ar:$CS_2$and Xe:CS_2gas 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 [14,15].

IV. SIMULATIONS AND SENSITIVITY

The first DRIFT detector will have active volume of $\sim$1 m^3 in the form of two back-to-back TPCs sharing a common cathode within a common vacuum vessel. The gain structure in each TPC will be a multiwire proportional chamber (MWPC) with 20 (100)μm anode (grid) wires spaced at 1 mm. MSGD devices with back-side PGA output connection [16] are also under consideration. The fiducial region for WIMP recoil events is the volume between the cathode and the grid wires. Part of the grid will be read out along with the anodes, to form a veto region several centimeters wide around four sides of the fiducial region. Ionizing radiation entering from these sides will thus be efficiently vetoed. Ionizing radiation entering from the top and bottom can also be vetoed since in passing through the MWPCs, it produces a characteristic fast pulse shape (due to the high electric fields there).

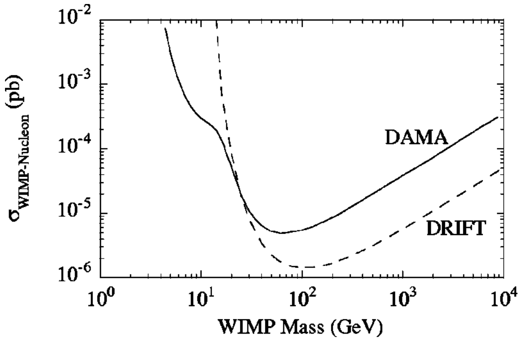

FIG. 1. Upper limits (90% c.l.) on the spin independent WIMP-nucleon interaction cross section obtained by the DAMA collaboration in comparison to the sensitivity of DRIFT after one year of running. Halo parameters and coherence parametrizations were identical. The DRIFT threshold for this calculation was 40 keV.

To assess the sensitivity of the DRIFT concept a Monte Carlo simulation was run modeling a detector filled with pure Ar. Argon was studied simply because a Monte Carlo study requires range-energy and ionization data for low energy ions which are available for only a few gases, including Ar [17]. Pure Ar would not actually be a suitable fill gas; ^{nat}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 the main isotopes have zero nuclear spin. Obtaining range-energy data for more suitable gas mixtures is a high priority for the DRIFT collaboration, but initially studies of Ar may still be taken as illustrative of the DRIFT concept.

The gas pressure was taken as 40 Torr, to make the range of a typical WIMP recoil long enough to be measured using anodes spaced at 1 mm. The rate of Ar recoils in the 1 m^3 DRIFT detector having energy greater than 40 keV was calculated as a function of WIMP mass. Some results are shown in Fig. 1. The curves show the upper limits on the WIMP-nucleon (spin-independent) scattering cross section if zero nuclear recoils were detected in one cubic meter of 40 Torr Ar in one year. At large WIMP masses, this simulated limit curve is roughly $\times 5$ stronger than the experimental upper limits previously cited in Ref. [18] by an author of Ref. [8], despite the mass of Ar in the simulated detector being only 0.094 kg. The zero-background limit would continue to improve as 1/t until the exposure reached the order of 1/ABG. Thus high sensitivity can still be achieved with a very low target mass if the backgrounds can be sufficiently reduced. The reasons to believe that zero background is achievable in DRIFT are discussed next.

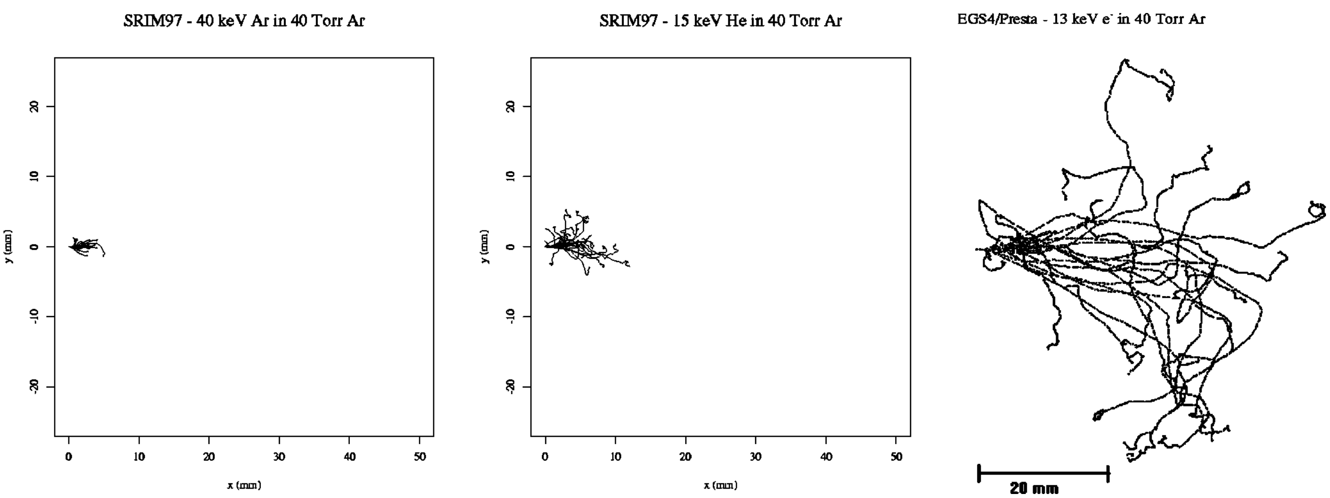

FIG. 2. The figures above show, from left to right, 40 keV Ar recoils, 5 keV alphas, and 13 keV electrons in 40 Torr Ar.

V. BACKGROUND REJECTION EFFICIENCIES

Experience has shown [19] that it is practically impossible to keep all background radiation out of the detector volume. To achieve the sensitivity indicated above, those background events which do occur must be rejected with very high efficiency. This rejection is obtained through event-by-event measurement of total ionization as well as several, if not all, components of the recoil range. Detailed simulations of rejection efficiency for different types of background events have been performed; the results are discussed in the following paragraphs.

One major source of background in DRIFT is ~MeV alpha particles from radionuclides of the U and Th series. Undegraded MeV alphas have ranges of tens of centimeters and deposit hundreds of times more ionization than WIMP recoils. Furthermore alphas which enter the fiducial volume from the sides will be vetoed as discussed above. The dangerous background arises from alphas originating within the grid wires or cathode. These evade the veto regions and may lose enough energy emerging from the wires and cathodes to produce total ionization similar to that allowed for WIMP recoils. For example, in 40 Torr Ar, 500 primary ion pairs are produced by either a 15 keV alpha particle [20], or a 40 keV Ar recoil [21]. But the alpha particle has a range of about 17 mm [20], while the Ar recoil range is only 2.7 mm [17]. Considering only the range is an oversimplification since as shown in Fig. 2, alphas do not travel in straight lines at these energies. However, our detailed SRIM simulations show that even such energy-degraded alpha particles can still be efficiently rejected. The Ar recoil and alpha tracks used for our simulations and shown in Fig. 2 were generated with the SRIM97 Monte Carlo program [22] scaled to match experimental range-energy data of Refs. [20,21]. Using cuts on just *two* components of the range with SRIM-generated tracks, an alpha mis-identification probability (MIP) less than 5% is obtained with negligible loss of Ar tracks. More sophisticated cuts or measurements of the third dimension will allow for even better alpha rejection.

Misidentification probabilities for electron events in DRIFT are even lower. Electrons arise from photon Compton interactions within the fiducial volume or from non-vetoed betas entering the fiducial volume from the grid wires or the cathode. Again for purposes of illustration, consider an event with 500 primary ion pairs. This would be produced by either a 13 keV electron with range ~85 mm [23], or by the 2.7 mm Ar recoil discussed above. As with alphas, the electrons do not travel in straight lines, as shown in Fig. 2 for 13 keV electron tracks simulated with EGS or PRESTA [24,25]. Simulation with EGS or PRESTA tracks show that cuts on just two components of the range give an electron MIP less than 3×10^{-5}. Again more sophisticated cuts or measurements of the third dimension will allow for even better electron rejection.

There is no rejection factor for neutrons since the recoils they produce can be identical to those produced by WIMPs. To reduce the rate of neutron interactions in DRIFT to one or less per year, adequate shielding and a low background environment must be provided.

Using our prototype NITPCs we have measured, in two dimensions as discussed above, the ionization produced by photoelectrons, Compton electrons, alpha particles and neutron recoils. Preliminary results indicate an alpha MIP less than 5% and an ^{55}Fe (6 keV) x-ray MIP less than 0.001, in agreement with our predictions above.

VI. BACKGROUND RATE ESTIMATES

Using the expected electron and alpha MIPs, the ABG rate in DRIFT can be estimated. For alphas the most important consideration is the radiopurity of the wires and the cathode. We have had tested commercially available stainless steel wires with U and Th concentration less than 0.5 ppb [26]. Acrylic to form the central cathode can be had with U and Th contamination less than 0.01 ppb [27]. The upper limits on the radiopurity of these elements and the 2D range-ionization MIP for alphas give an upper limit of the order of 10 events per year from alpha background in DRIFT. Thus if the actual radioactivity levels do turn out to be near the measured upper limits, somewhat better rejection may be needed. Further highly effective reduction strategies are under study.

Electron backgrounds can be estimated using published flux measurements of gammas inside operating dark matter shields [19] and measurements of beta and gamma emitters in various construction materials. These estimated levels combined with the 3×10^{-5} upper limit on the MIP for low energy electrons give an estimated ABG from electrons of less than 0.03 events per year.

There is no rejection factor for neutrons, but neutron flux measurements in the intended underground site yield an expected neutron recoil rate well below 1 event per year [19].

To summarize, detailed background estimates with rejection factors confirmed by experiments in NITPC prototypes lead to a reasonable expectation that DRIFT can achieve the ''zero-background'' sensitivity discussed above.

VII. WIMP DETECTION SIGNATURE

In addition to having good sensitivity, the DRIFT detector also has a very robust signature for *detecting* WIMPs. WIMP signatures in direct detection experiments [10] arise from the fact that the solar system rotates around the center of the Galaxy, through a halo of WIMPs generally believed to be *non-co-rotating*. WIMP velocities relative to the Earth are therefore a combination of the WIMPs 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 (toward R.A. 21hr 12.0′, Dec. +48.19°) is roughly in the direction of the constellation Cygnus. Thus 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 [10]. From April to September the Earth's orbital velocity around the Sun has a component toward Cygnus (''into the wind''), producing higher energy recoils at a higher rate than during the months October–March, when the velocities are oppositely directed. For a threshold energy of the recoil, $E_{th}=0$ keV, this asymmetry (rate difference divided by the sum) is 2% while for $E_{th}=1$ keV/amu A it rises to 5%.

We have extended the work of Spergel [10] by performing a Monte Carlo simulation of the recoils produced from 100 GeV WIMPs in 40 Torr Ar, including SRIM-generated [28] scattering of the Ar recoils and NITPC drift diffusion. The simulation shows that the measured $\Delta\tau=|\tau_{recoil}-\tau_{cyg}|$ will retain an asymmetric distribution peaked near 0°, due to the preferred axis of the ''WIMP wind'' effect. To test a dataset of accepted events for the presence of the WIMP wind signature, form an asymmetry between recoils with $\Delta\tau$ less than 45° and those greater than 45°. This asymmetry should be zero for any terrestrial background. The simulation described above predicts that for a pure sample of WIMP recoils in DRIFT with $E_{th}=0$ keV the measured asymmetry would be 7%, while for $E_{th}=1$ 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.

These asymmetries provide a very robust WIMP signature. To achieve any given confidence level of detection through measurement of an asymmetry, the figure of merit (FOM) of an experiment is proportional to $FOM \propto a^2 N_{WIMP}/(1+N_{\mathrm{background}}/N_{\mathrm{WIMP}})$ where N_{WIMP} is the number of WIMP events detected and $N_{background}$ is the number of background events detected. Groups seeking to identify WIMPs through the small annual modulation asymmetry and with large ABG rates require a correspondingly large number of real events. This implies large detector mass and long exposure to achieve a given figure of merit. However, larger asymmetry and lower background can make the number of events needed (and hence the required exposure) orders of magnitude smaller.

For example, the authors of Ref. [8] reported a signal consistent, at the 90% confidence level, with detection of an annual modulation. This implies ≈85 000 *real 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 confidence level with only 140 WIMP events, i.e., with ≈500 times less exposure. Detecting a sidereal-rate modulation is also less demanding experimentally than an annual one. The sidereal 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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