Negative Ion TPC for WIMP Astronomy

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Most of the matter in galaxies and galaxy clusters is of a composition unknown to science. Terrestrial experiments are underway to search for this matter if, as is widely believed, it is composed of undiscovered heavy, stable particles left over from the Big Bang. Directional signatures for interactions of such particles result from the motions of the earth in space. While difficult to detect, these signatures provide the only unambiguous ways to associate terrestrial events with the cosmos. This contribution proposes a modular detector design with sufficient mass and directional sensitivity for a cutting-edge search-and-discovery experiment for WIMP dark matter.

1. Motivation for Particle Physicists

The celebrated confluence between elementary particle physics and astrophysics[1] has one of its principal nodes in the subject of WIMP Dark Matter. Astronomy and astrophysics provide a number of independent lines of observational evidence pointing toward the existence of a very substantial unidentified gravitating mass component in galaxy-sized and larger systems. This material is believed to make up over 85% of the *mass* density of the universe[2]. Observationally, it does not interact with electromagnetic radiation, hence the term Dark Matter. Supersymmetry in particle physics provides a strong suggestion for the nature of such matter in the form of heavy stable particles which are expected in most variants of that theory[3].

To satisfy observational and experimental constraints as well as theoretical expectations, the dark matter particles must interact very weakly with ordinary matter. In fact the interaction strength and the present-day mass density for a Big Bang remnant are related by the Lee-Weinberg bound[4, 5]:

$$\Omega_{DM} h^2 \sim \frac{0.1\mathrm{pb}}{\langle \sigma_{\mathrm{ann}} \beta \rangle}. \tag{1}$$

Here Ω_{DM} is the present day relic mass density scaled to the "closure" density of General Relativity, h is the reduced Hubble Constant, σ_{ann} is the annihilation cross section for the relic particle with its antiparticle, and β is the rms thermal speed of the relics at the time they decouple. According to this relation, *any* massive stable particle that exists in nature *will have* a calculable relic density. To give a relic density of the order of magnitude indicated by observations (which happens to be within a factor of a few of Ω_{DM} = 1), the interaction cross section of the relic particles comes out compellingly in the range of typical weak interactions of SUSY particles.

2. Observing WIMP Scattering in the Lab

2.1. Characteristics of the Interactions

The combined relative motions of the WIMPs making up our galaxy's halo, and the Earth in the galaxy's gravitational field, afford a mechanism for observing these very weakly interacting particles using recoil atoms produced by elastic scattering of the WIMPs on atoms of a suitable detector. Techniques for such "direct detection" experiments have been reviewed[6, 7]. *Direction sensitive* detection of the nuclear recoils allows their directional distributions to be correlated with the known motions of the earth in space, yielding a definite signature confirming the extra-terrestrial origin of any detected events. The directional signatures have an extensive literature[8–10].

For the simplest model of galactic halo WIMPs (Boltzmann distributed energies with velocity cutoff at a few times v_{rms} by gravitational escape) the energy distribution of recoil atoms is a decreasing exponential with a characteristic energy that depends on the relative masses of target nucleus and WIMP, but is always of the order of tens of keV[11]. Such recoil atoms have ranges in matter of only a few tens of micrograms/cm^2. The resulting short tracks can only be directionally measured with a gas detector operating at reduced pressure and suppressing diffusion by drifting negative ions at very high drift field[12] (but see also [13, 14]). For example, in the DRIFT NITPC[15] with 40 Torr CS_2 fill, WIMP recoil tracks would be of the order of millimeters in length.

2.2. Direction Sensitive Detector Characteristics

But low pressure by itself is not enough. Present day non-directional dark matter detectors [16–20] have sensitive masses of the order of kilograms. To attain a competitive sensitive mass with reduced pressure gas requires e.g. volumes of the order of 10 m^3. The ultra-low background needed for dark matter work requires a TPC geometry in which only gas is present in the fiducial volume. But these two requirements together with the short track lengths place stringent requirements on diffusion, which are impossible to meet with conventional electron-drift TPC's. The negative-ion TPC [12, 15] allows diffusion to be suppressed to the thermal limit ($700\mu\mathrm{m}\sqrt{\frac{L_D(m)}{V_D(KV/cm)}}$ while applying very high drift fields (tens of V/cm Torr) without diffusion runaway due to electron heating.

The final piece of the puzzle is an affordable readout method capable of resolving submillimeter tracks over several square meters of endcap. This is quite different from the usual high energy physics requirements of accurate sagitta determination and good double track resolution. The occupancy in underground experiments is near zero, but the readout must discriminate short tracks from pointlike interactions down to the diffusion limit.

The low occupancy permits interpolating-type readouts with affordable channel count to be used, if the required granularity can be achieved. However, the variety of signatures allowed by models leads to the desirability of a full three-dimensional track measurement rather than a projective one in which one dimension is sacrificed.

Another unusual characteristic of a dark matter TPC is that the negative-ion drift speed is fortunately very slow ($\sim$ 100 m/s/(KV/cm) at 40 Torr), allowing the use of quite slow digitizers (sampling intervals of order $\sigma_D/\mathrm{v}_{\mathrm{drift}} \sim 2.5$ μsec) without loss of track information.

Two readout schemes can be envisioned which satisfy the above requirements. Actually one of the schemes "cheats" in that it actually only measures two track projections and infers the third from the total track length deduced from the ionization. Both schemes rely on conventional wire-plus-pad endcap structures, although adaptations to micropattern detectors could be devised. Micropattern detectors are known to work with negative ion gases[21].

In the first scheme, the TPC endcap MWPC consists of highly isochronous drift cells with 2 mm wire pitch, 5 mm gap and 2 mm wide pads. Each wire and each pad is equipped with a $\sim$ 1 MHz transient digitizer.

The projection of each short track along the drift (z) direction is inferred from its duration in time, even when the track is fully contained in a single drift cell. To permit this inference without independent information on the transverse location of the track within the cell, the cell must be higly isochronous. An enlightening discussion of isochronous drift cells is given by Va'vra in Ref.[22]. Figure 1 shows a cell adapted from an example in that work, which is isochronous to a degree equivalent to 250 μm in the z position. This is smaller than the 500 μm rms diffusion expected during a 1 meter drift in CS_2 at 2 KV/cm, and hence is satisfactory.

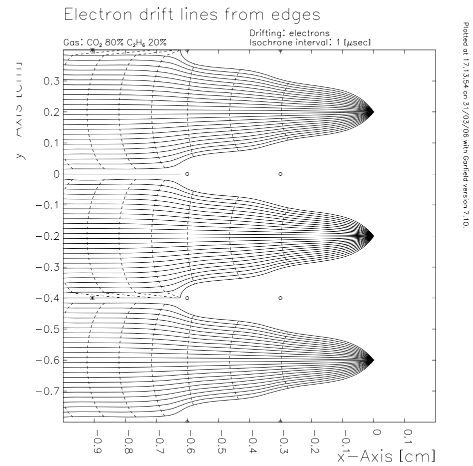

Figure 1: GARFIELD plot of isochronous drift cell, developed from Ref. [22]. The cell consists of three wire planes of equal pitch, two of them for field shaping and the third of anodes. Drift lines and isochrones are shown. The small curvature of the isochrones in the homogeneoud field region shows that this arrangement has an extremely linear space-time relation for the z (drift) coordinate.

The track projection along the wire (y) is measured using the pad readout in a manner described in Ref.[23]. This basically consists of using the digitized pad waveforms to compute a y-centroid for every time- (hence z-) slice. Submillimeter resolution in y was achieved in Ref.[23] for each time slice. With the extent of the track thus measured along two coordinates, and the total track length known from range-energy relations[24], the third component of a WIMP recoil track could be computed and the direction known.

This method is straightforward but it relies on the geometrical assumption of a perfectly straight track to carry out the third-coordinate recovery. For these recoils (e.g. carbon in CS_2) the probability of large angle scattering during the stopping is not small.

All three track components can be measured if the digitized wire- and pad-readout is augmented by an additional set of pickup electrodes that measure $x(t)$ directly. This was shown to work by Nygren in his Radial Drift Chamber concept[25] but never used in an experiment up to now. The electrode geometry is shown in Figure 2.

Between each pair of anode wires lie a centrally-located field-shaping wire and two pickup wires very

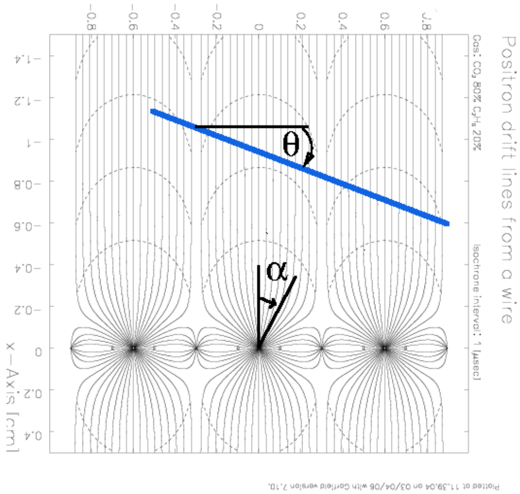

Figure 2: GARFIELD plot of radial drift chamber cell after Nygren[25]. A (long) track is shown making an angle θ to the wire planes. The single plane of wires consists of anodes, field-shaping wires halfway between each pair of anodes, and a pair of pickup wires flanking each anode.

close (300-500 μm) to the respective anodes. With the appropriate potentials and a low-diffusion gas, the x coordinate at which ionization originates uniquely determines their arrival angle α at the anode. This angle is determined in a time-resolved fashion from the digitized difference in induced signals on the two pickup electrodes around each anode. Prototype measurements reported in Ref.[25] gave x resolution better than a tenth of the cell width. For the present application anode wire pitch of 4-5 mm would be used.

The x information also locates the track transversely within the (non-isochronous) cell. The correct portion of the space-time relation can therefore be employed for the z-reconstruction. All three components of a short track thus could be directly measured with submillimeter accuracy

3. Simulations of WIMP Astronomy Measurements

The "angular resolution" of a direction-sensitive WIMP TPC is not just a function of detector parameters. It is also determined by a combination of the elastic scattering kinematics (i.e. mass ratio of WIMP to target atoms) and the relative speeds of the solar system in its orbit around the galactic center vs. the WIMP's rms thermal motion, and any local streaming motion the WIMPs may have. All the factors relating to the WIMPs are of course unknown. The resolution of a proposed detector should be discussed in terms of its ability to distinguish specific WIMP halo hypotheses from one another.

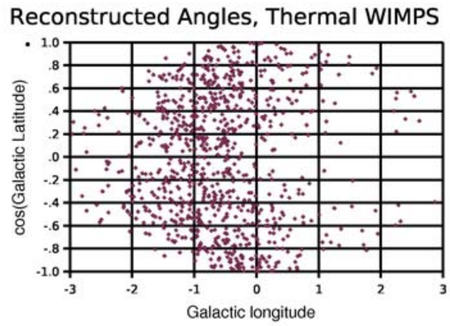

Figure 3: Reconstructed galactic coordinates of WIMP recoil directions assuming detector parameters and WIMP halo parameters as discussed in the text, for a Boltzmann distribution of WIMP velocities, plus the solar system's motion through the halo.

As an indication of the power of the detector discussed here, simulations of two extreme cases of WIMP halo dynamics are presented below. For each case the WIMP mass is assumed to be 100 Gev/c^2. The two cases compared are the "standard" halo parameters of Ref.[11] (Boltzmann distribution with v_{rms} = 220 km/sec, cut off at 660 km/sec), and a model in which the WIMP motion is just a stream with uniform velocity 1000 km/sec.

The simulation program included longitudinal and transverse range straggling, track diffusion with $\sigma_D = 770\mu\mathrm{m}\sqrt{\mathrm{L}(m)}$, and wire trigger thresholds. The readout was assumed to be oversampled at 100 μm in z and with 100 μm uncertainties in the transverse coordinates. Track direction cosines were reconstructed by fitting a line through the time-slice position measurements. Still missing from the simulation are large angle scattering of the recoil atoms, and a full treatment of readout noise including avalanche fluctuations and calibration variations.

A key assumption was that the beginning and end of a track were distinguishable, using a combination of the decrease of dE/dx with decreasing energy in this energy range, and the multiple scattering of stopping ions. Analysis by this author of well-sampled (i.e. long) neutron-recoil tracks in DRIFT I calibration data strongly suggests that this is achievable with sufficiently dense sampling of the tracks.

Figures 3 and 4 show the distribution in galactic longitude vs. (cosine of) galactic latitude for 1000 reconstructed carbon recoil events. The distributions are clearly significantly different from one another and from an isotropic distribution. The reconstructed event distributions for Boltzmann WIMPS is statistically distinguishable from isotropy at the 90% CL with less than 20 events. For the fast WIMP stream, just a handful of events suffice.

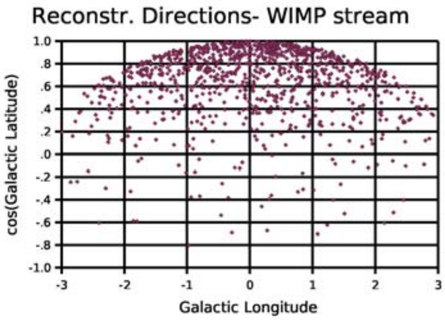

Figure 4: Reconstructed galactic coordinates of WIMP recoils assuming detector parameters and the high-velocity WIMP stream discussed in the text, plus the solar system's motion through the halo.

4. DM-TPC Design

4.1. Detector Modules

Figure 5 shows a conceptual design for a prototype or a single module of a competitive Dark Matter TPC. The active volume is 24 m^3. The 4-meter height of the module is chosen to fit each hexagonal wire frame whole into the WIPP waste hoist. The smaller hoists at other sites would require constructing the frames out of independent triangular subassemblies as shown and assembling these underground.

The central cathode would run at 200(100)KV to provide a drift field of 2(1)KV/cm in 80(40) torr CS_2 (4(8) kg active target per module). Such a high drift field is known to work in this gas at these pressures. The drift speed would be $v_d = 200\mu m/\mu sec$ and rms diffusion $\sigma_D = 500(700)\, \mu m/\sqrt{m}$.

The anode wire count per endcap would be 2600 at 4 mm pitch, and there would be 5475 cathode pads 8 mm x 160 mm. The total number of digitizers would therefore be 10,675 per endcap. A set of VME boards each carrying 32 independent channels of preamp-plus-digitizer at 1 MHz sampling rate was designed and built at SLAC for DRIFT I, at a cost of under $90 per channel[26].

Modules would be placed in an end-to-end array to construct a full detector. Several hundred kilograms of active material would easily be accommodated in WIPP, including the necessary local shielding. In such an array of modules, each endcap detector could view two back-to-back drift spaces, if wire planes were used to replace the y-measuring pads.

4.2. Local Shielding Requirements

Experience with DRIFT I[15] shows that an NITPC has very strong discrimination against beta and gamma activities in the detector and the surroundings. The device is basically insensitive to gamma radiation. A "WIMP" trigger selecting events with only one or a few adjacent wires having primary ionization of several hundred electrons (100 primaries corresponds to about 5 keV recoil kinetic energy), results in a raw trigger rate for the unshielded detector at 3000 mwe of less than 2 per minute. Low gas density and the low LET of these forms of radiation results in probabilities less than or of the order of 10^{-5} for misidentifying beta or gamma interactions as nuclear recoils. Low-radioactivity construction techniques are still necessary for experiments aiming at interaction rates in the SUSY range but need not be as elaborate as in some other detector types with more limited discrimination.

However, neutron interactions in any WIMP detector will produce nuclear recoils that are individually indistinguishable from WIMP scatters. Therefore even in underground laboratories, local shielding against neutrons from the mine rock is needed for experiments with competitive sensitivity[27].

The underground neutron background has several components including a soft contribution from (α,n) interactions due to Uranium and Thorium alpha emitters in the rock and construction materials, and hard components produced by residual cosmic ray muons. The soft component is effectively eliminated by thermalizing it in a few tens of cm of suitable, radio-pure hydrogenous moderator. The hard component is simply too penetrating to shield effectively with a reasonable thickness of material, and in any case would be regenerated within a massive shield[28].

Very deep sites are one way to approach the low muon-induced neutron rates needed for experiments in the 0.1-1 ton range[29]. This is certainly an admissible solution for an NITPC of moderate size. However for a high-density detector like CDMSII[16] at a site of comparable depth to WIPP, a combination of hydrogenous shielding and and a highly effective muon veto has proved sufficient to set cutting-edge limits. Detailed Monte-Carlo studies[30] indicate that a very large ($\sim$100 kg) NITPC can achieve neutron background rates of just a few events per year at WIPP depth. A graded shield of Fe plus hydrogenous moderator incorporating a highly efficient neutron and/or muon veto was used in the simulations. The relatively numerous medium energy neutrons are inelastically scattered by the Fe with mimimum production of secondary neutrons. Secondaries and lower energy source neutrons are thermalized in the moderator. Higher energy neutrons must be vetoed either by their time association with a muon or upon entry or exit from the detector volume. Low mass and high radio-purity of the vacuum vessel are also of paramount importance in designing such a large detector for use at moderate depth.

Local shielding and vetoes will undeniably make up a significant fraction of the cost of a large NITPC. However it can be argued that the definitive signature

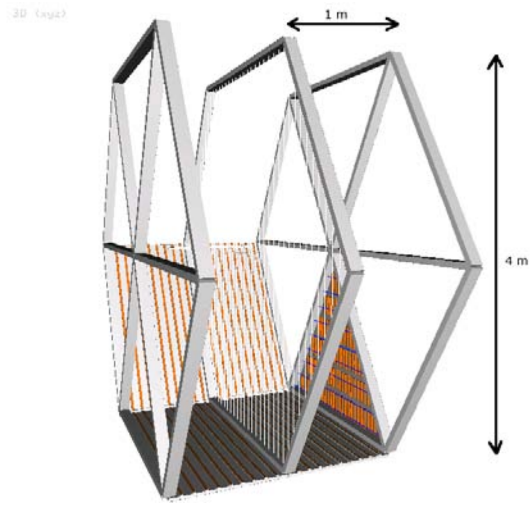

Figure 5: Schematic of 20 m^3 NITPC module discussed in the text.

afforded by direction-sensitivity makes such a project very compelling.

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